Status of the LUX-ZEPLIN Experiment

Direct Detection Search for WIMP Dark Matter

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SUSY 2022
On behalf of the LUX-ZEPLIN Collaboration

LZ (LUX-ZEPLIN) Collaboration

@lzdarkmatter

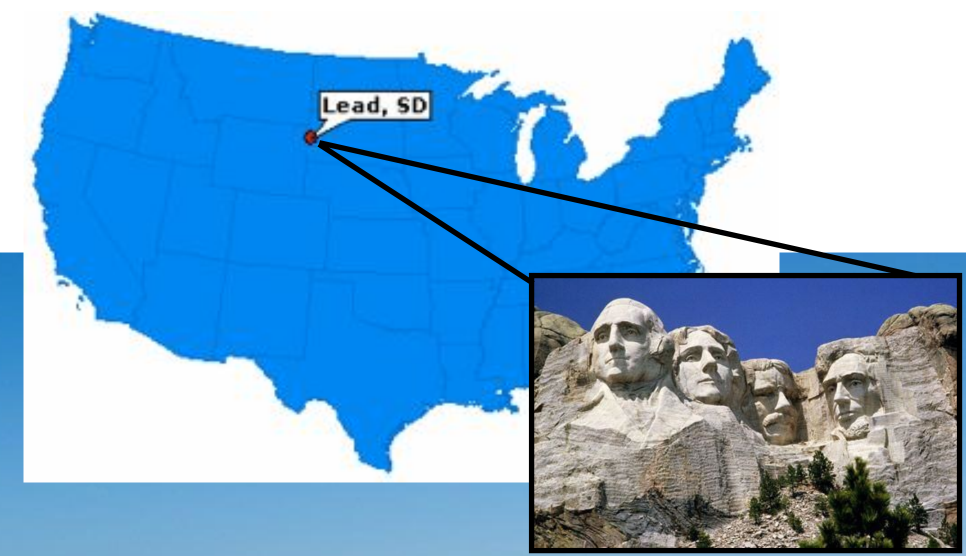
https://lz.lbl.gov/

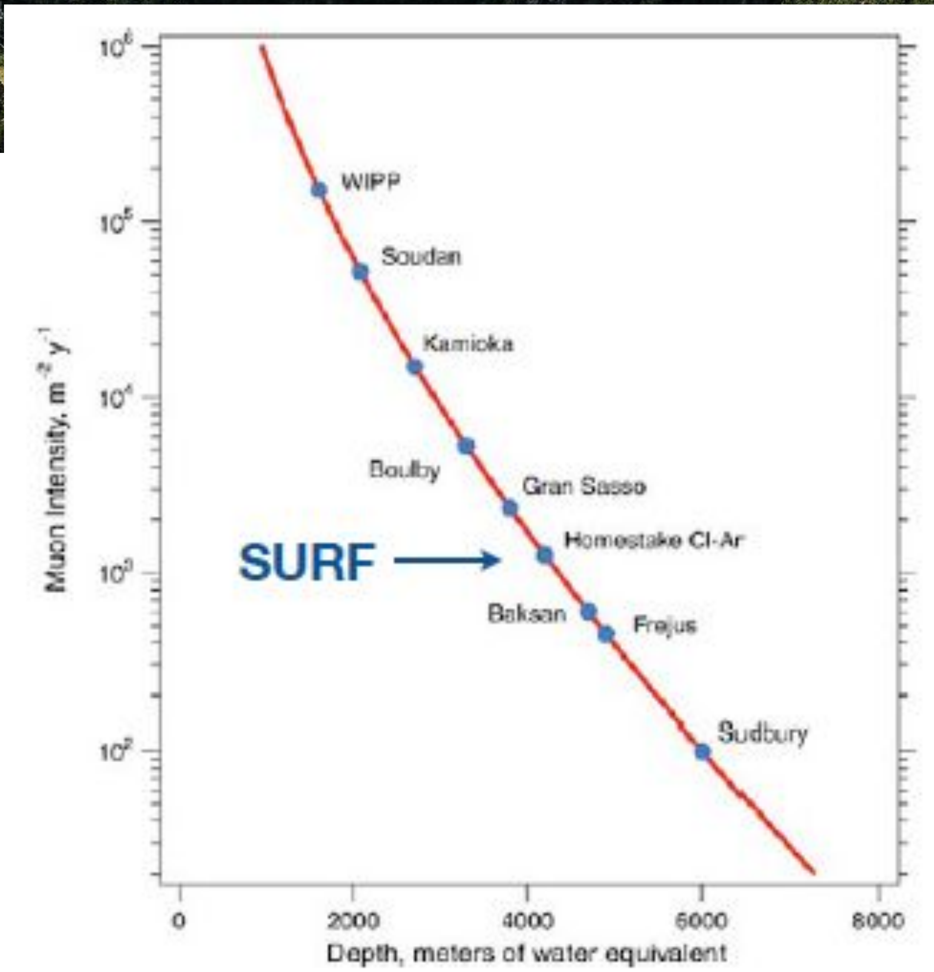
35 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison

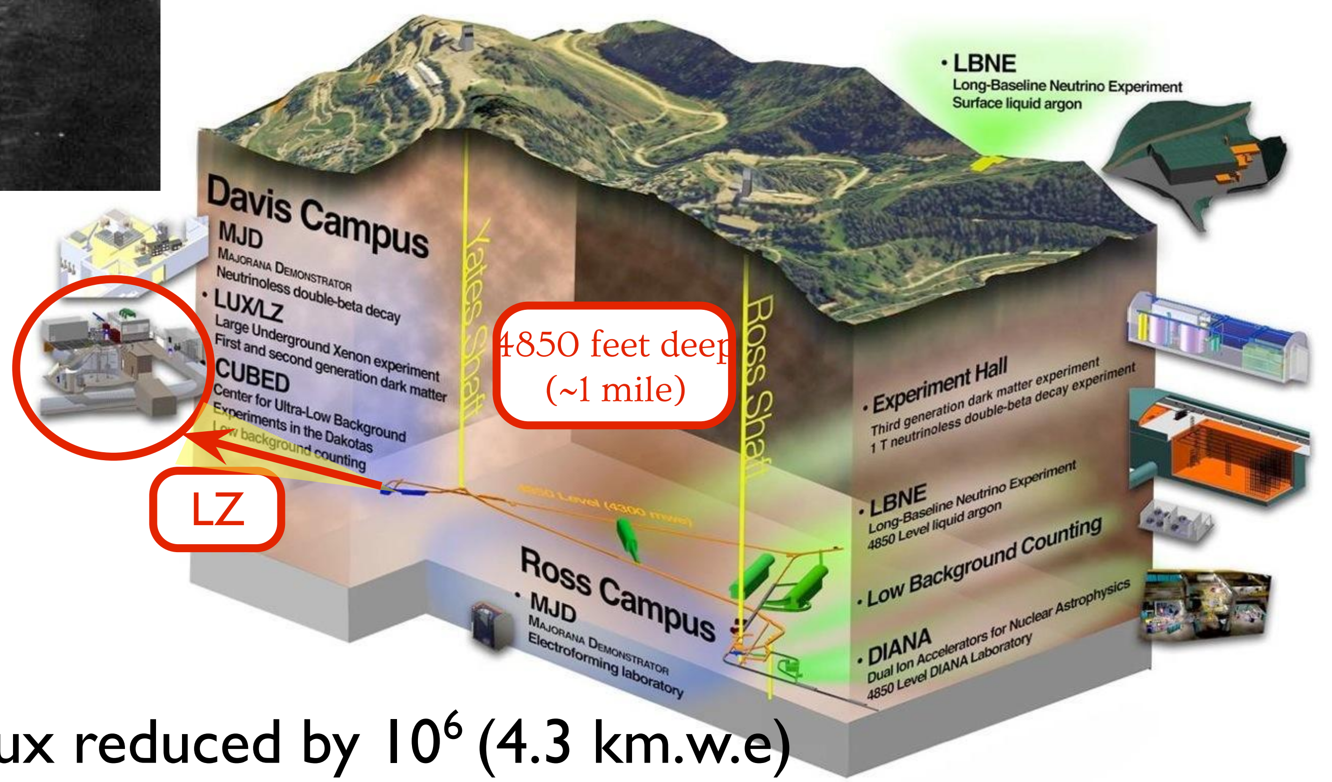
US UK Portugal Korea

Sanford Underground Research Facility (SURF) in Lead, SD





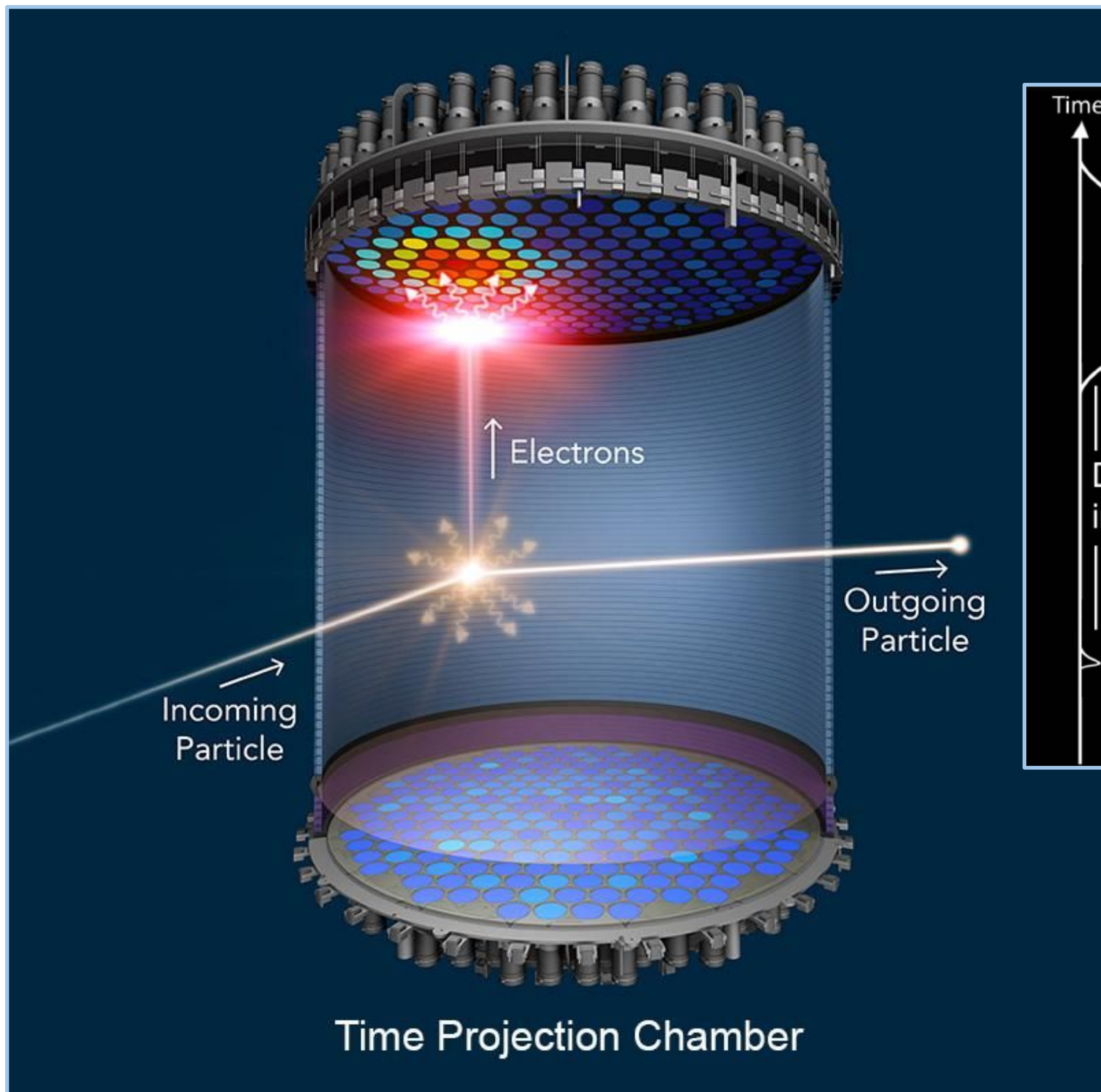
Ray Davis, Nobel Prize winner

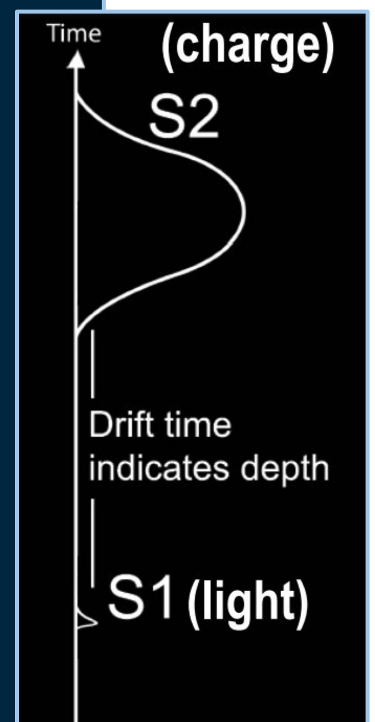


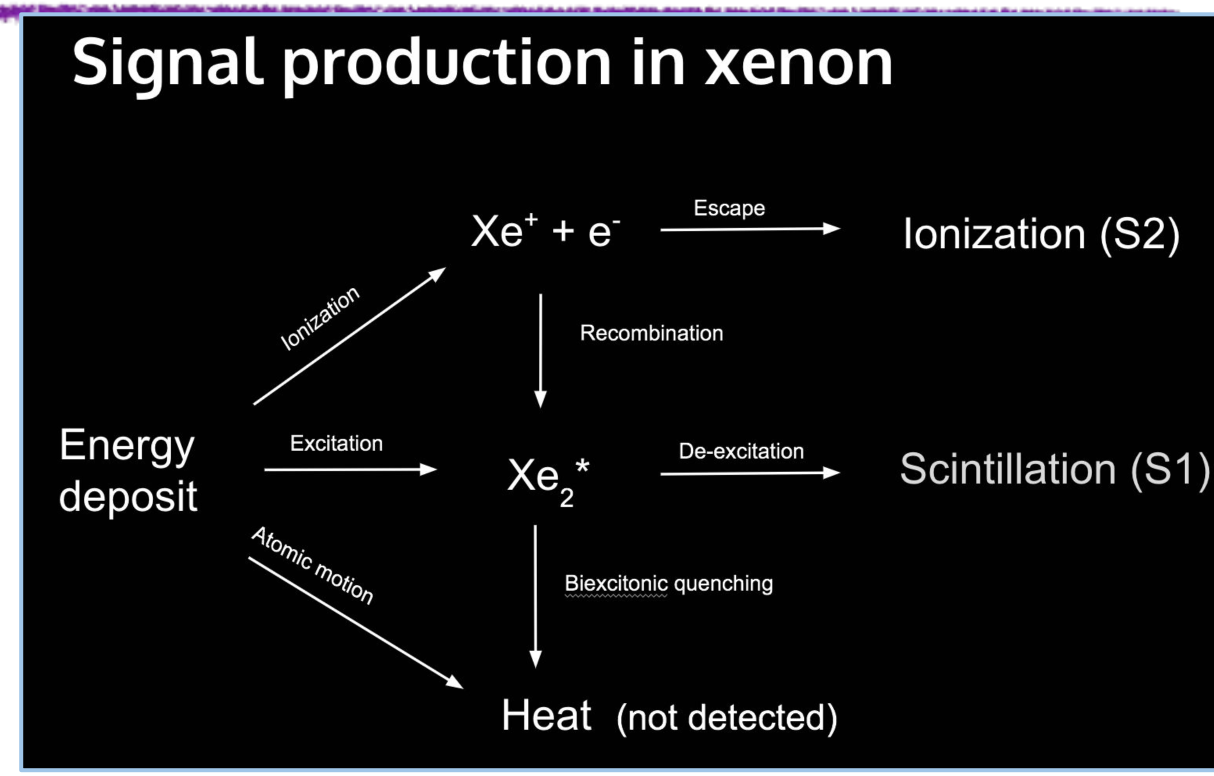
Muon flux reduced by 10^6 (4.3 km.w.e)

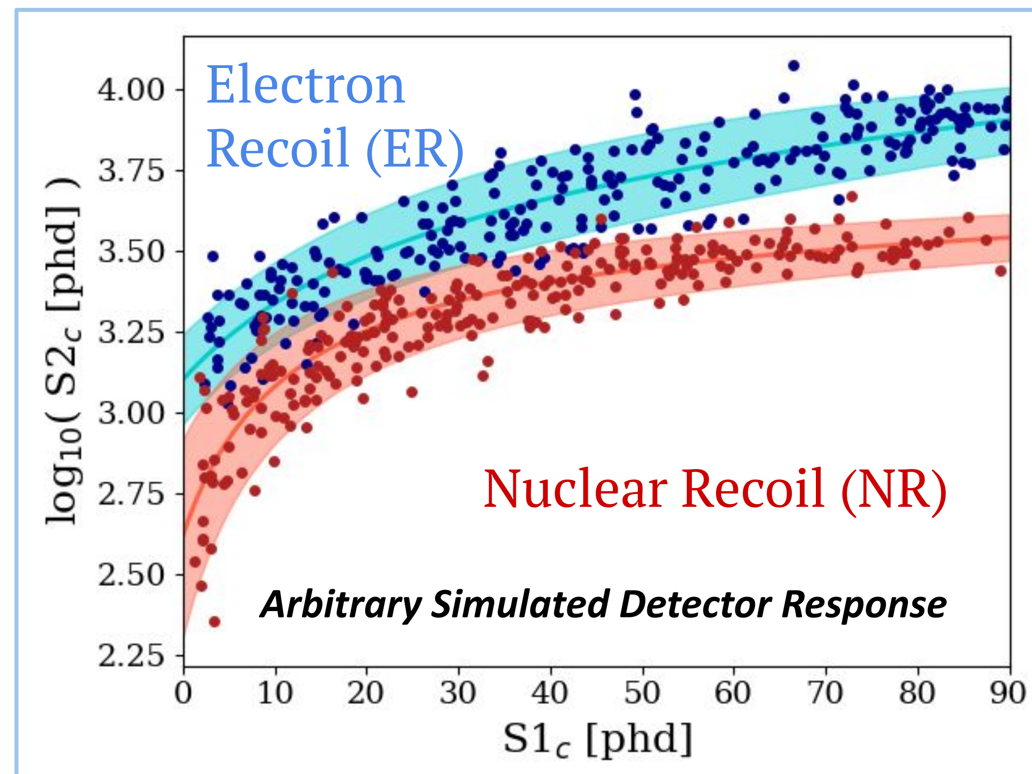
WIMP Direct Detection with a Dual Phase TPC

- *The Time Projection Chamber (TPC) allows for Reconstruction of the Number of Scatters, Interaction Position, and Energy*
- *Measures the Scintillation (S1) and Ionization (S2) response of LXe following an energy deposit*







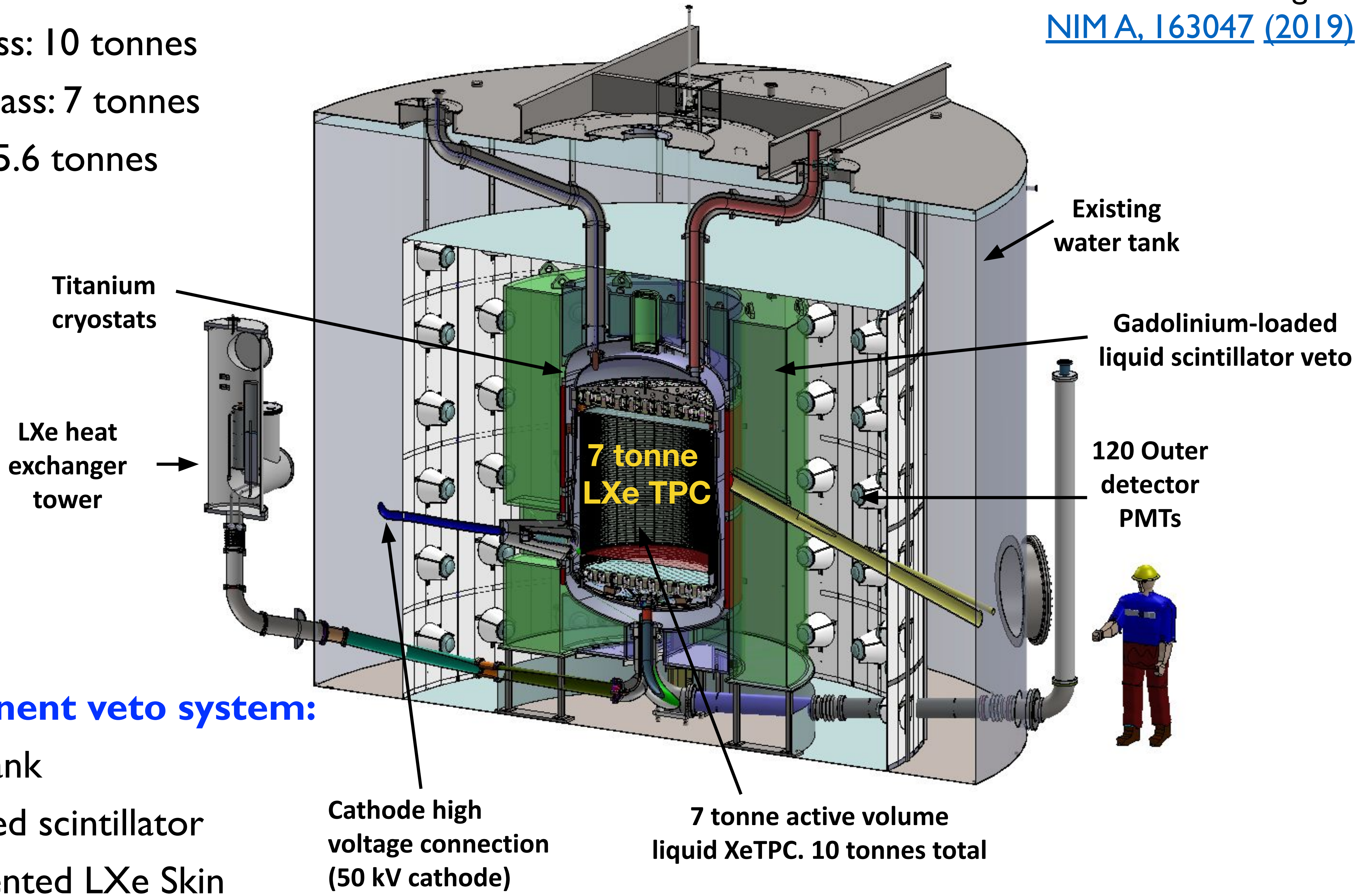


$$\langle \mathrm{S1c} \rangle = g_1 \langle n_{ph} \rangle \qquad \langle \mathrm{S2c} \rangle = g_2 \langle n_e \rangle \qquad E = \frac{W}{L}(n_{ph} + n_e)$$

LZ Detector Overview

- **Xenon TPC**
  - Total mass: 10 tonnes
  - Active mass: 7 tonnes
  - Fiducial: 5.6 tonnes

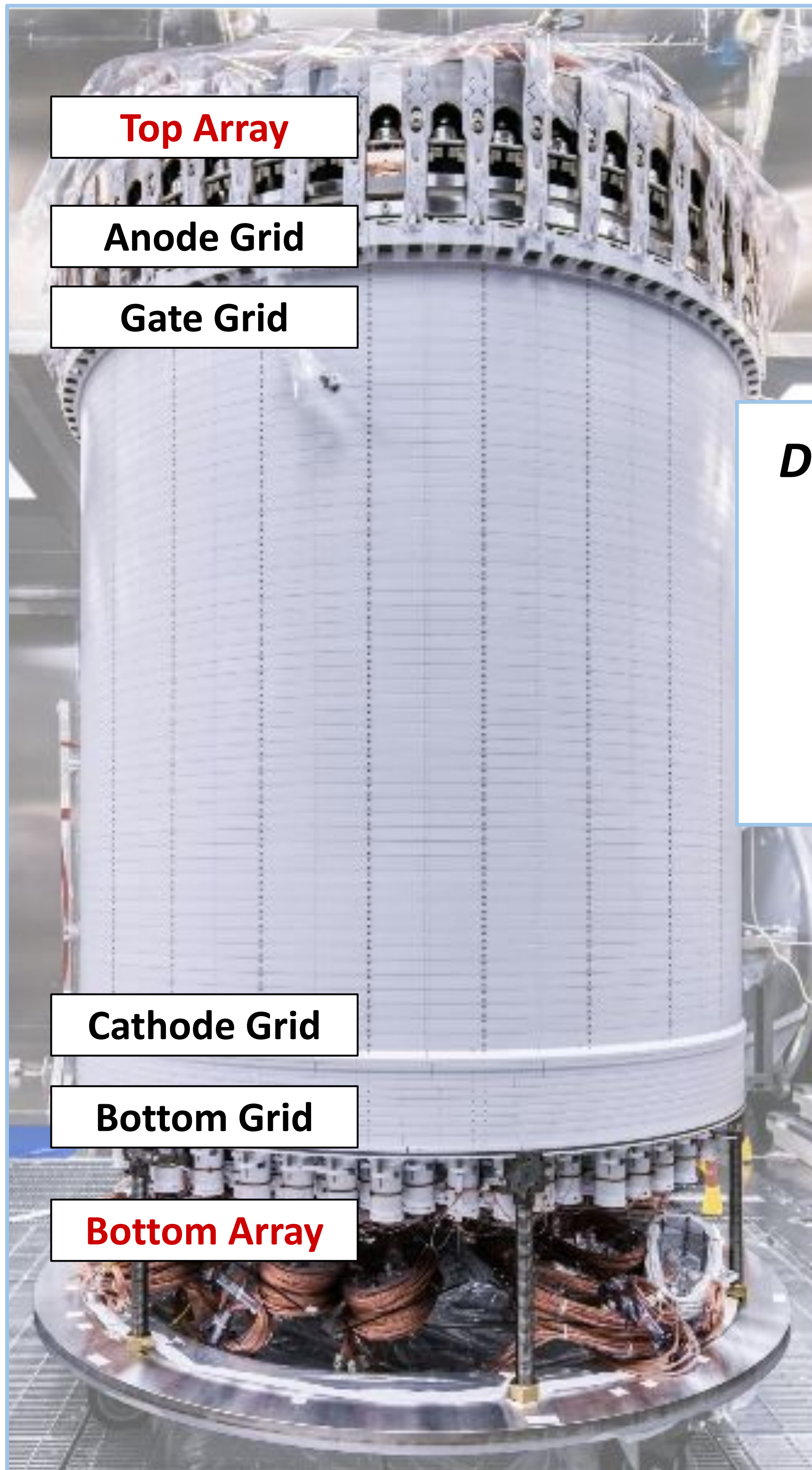
LZ detector design: NIM A, 163047 (2019)



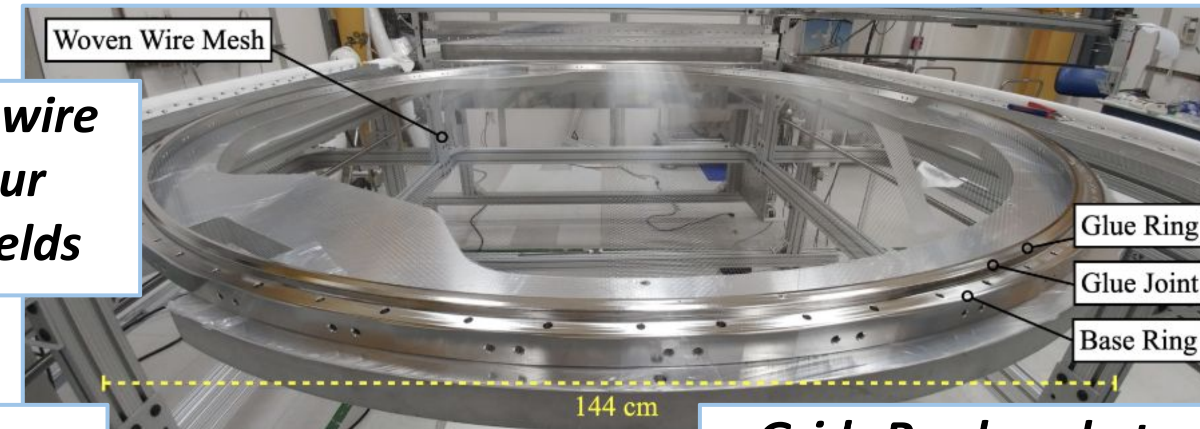
- **3-component veto system:**
  - Water tank
  - Gd-loaded scintillator
  - Instrumented LXe Skin

The TPC

1.5m Diameter, 1.5m Tall; 7 tonnes LXe



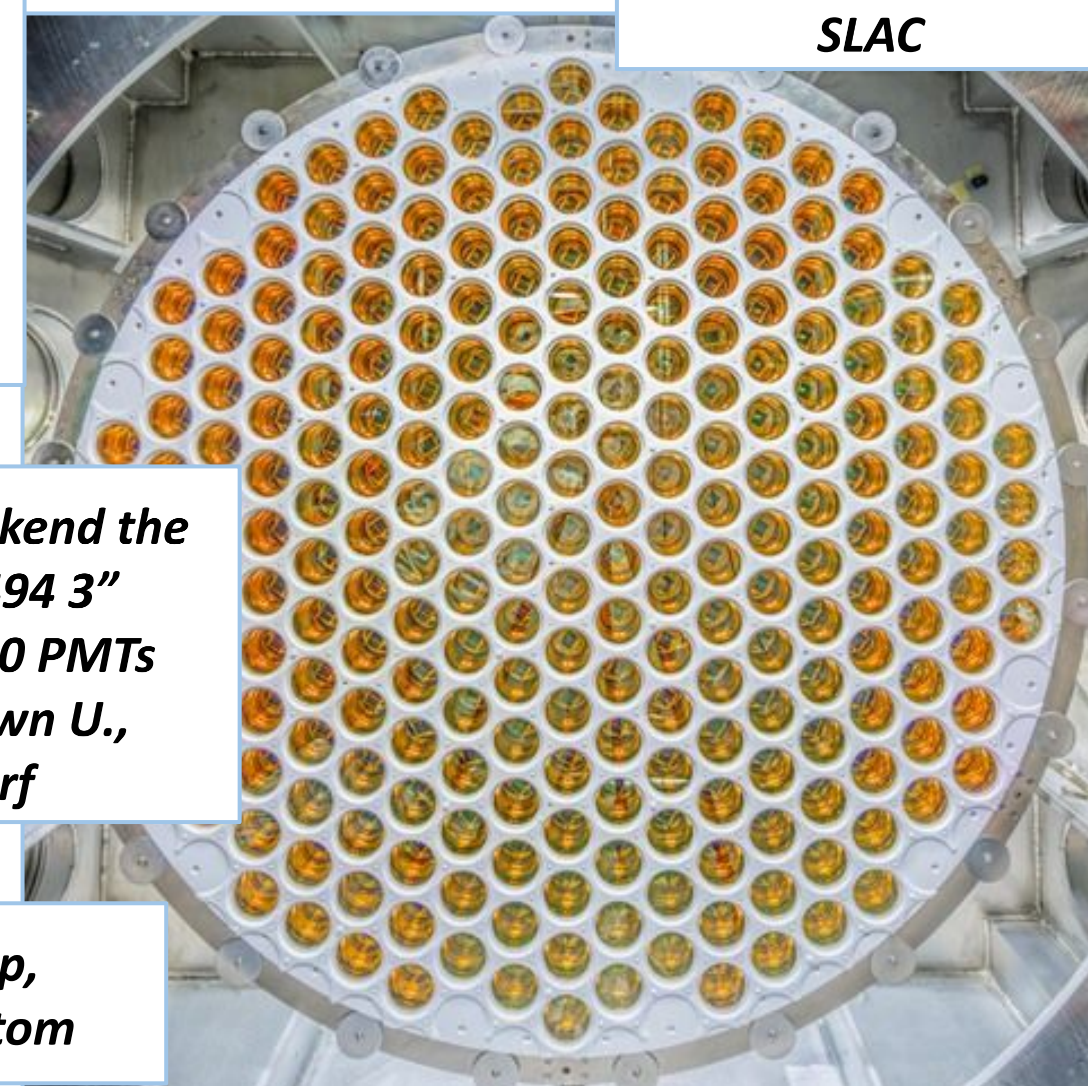
Four woven mesh wire grids creating our drift,extraction fields



Grids Produced at SLAC

Detector Integration: 13,500 Working Hours

TPC Assembled on the Surface, in a Rn-Reduced Class 1000 Cleanroom

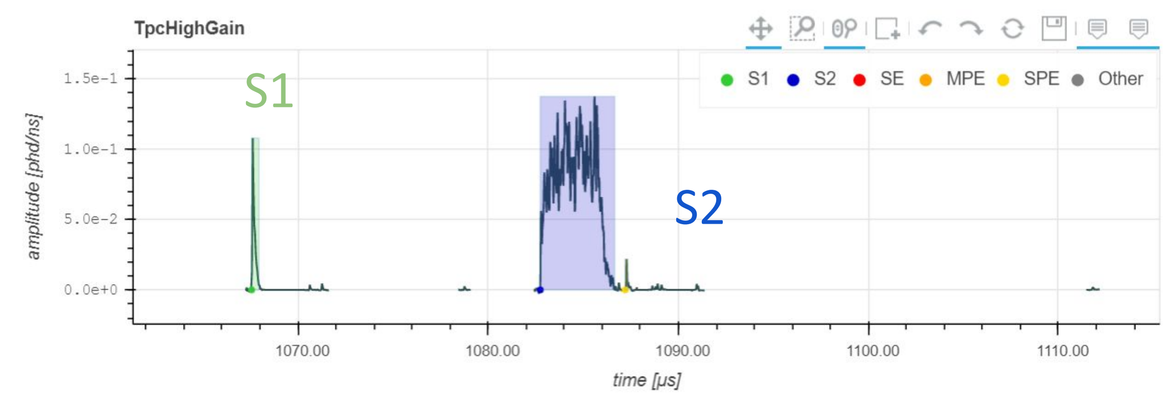


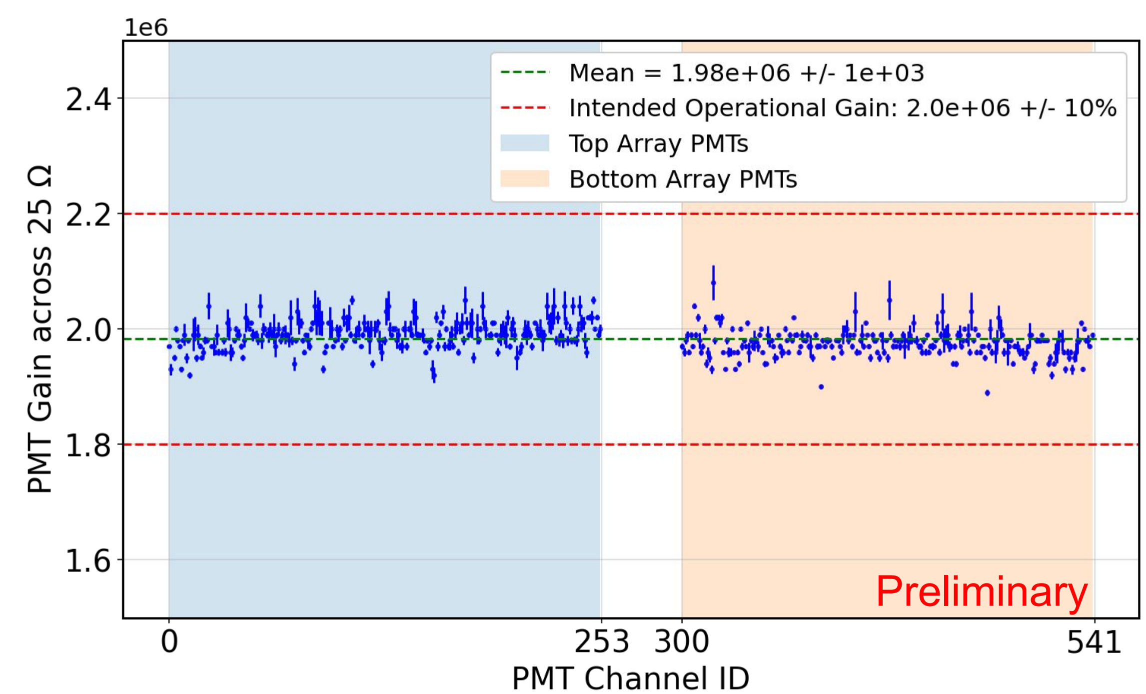
Two PMT arrays bookend the TPC, supporting 494 3" Hamamatsu R11410 PMTs Assembled at Brown U., Shipped to Surf

253 on Top, 241 on Bottom

LZ Commissioning

- TPC detector filled and leveled
- Grids biased: extraction & drift fields established
  - Drift field ~190 V/cm
  - Extraction field ~7.5 kV/cm gas
- Data processing chain exercised with first S1+S2s
- Data acquisition & trigger settings tuned
- PMT operations & characterization
  - LED measurements for after-pulsing and single photoelectron (SPE) studies
  - PMTs gain-matched and gain drifts monitored
  - Dark count & double photoelectron emission (DPE) analyses
- Event reconstruction algorithms highly reliable, with a Single Scatter identification accuracy >95%
- Application of machine learning to find anomalous events



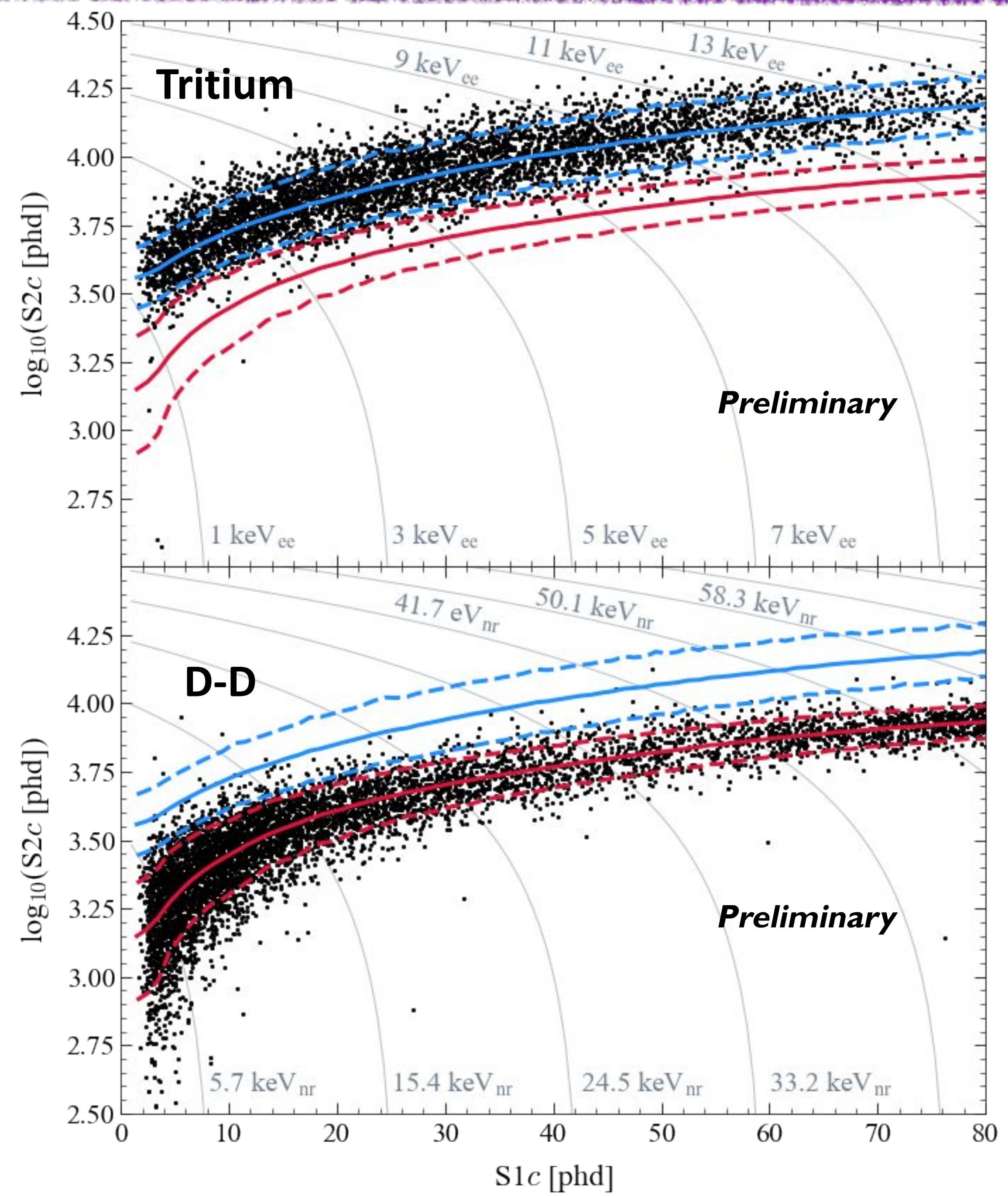


TPC Calibrations

- Have calibrated the detector with ^{220}Rn, ^{3}H, D-D, AmLi, ^{83m}Kr, and more!
- Injection of tritiated methane
  - ✦ Spatially homogeneous source of β ER, 0-18.6 keV
- External D-D fusion
  - ✦ Monoenergetic 2.45 MeV neutron beam
  - ✦ Up to 10^9 neutrons per second
- Tuning with The Noble Element Simulation Technique, NESTv2.3.7
  - ✦ Tuned to ^{3}H and D-D calibration data to provide the detector response model
  - ✦ g_1 = 0.1149 ± 0.0021 phd/photon
  - ✦ g_2 = 46.38 ± 1.51 phd/electron
  - ✦ Extraction Efficiency = 80.49 ± 3.72%

github.com/NESTCollaboration/nest

nest.physics.ucdavis.edu



Bands are the tuned NEST response for Tritium and D-D calibration sources; 90-10% CL Widths, Skew Gaussian Fits

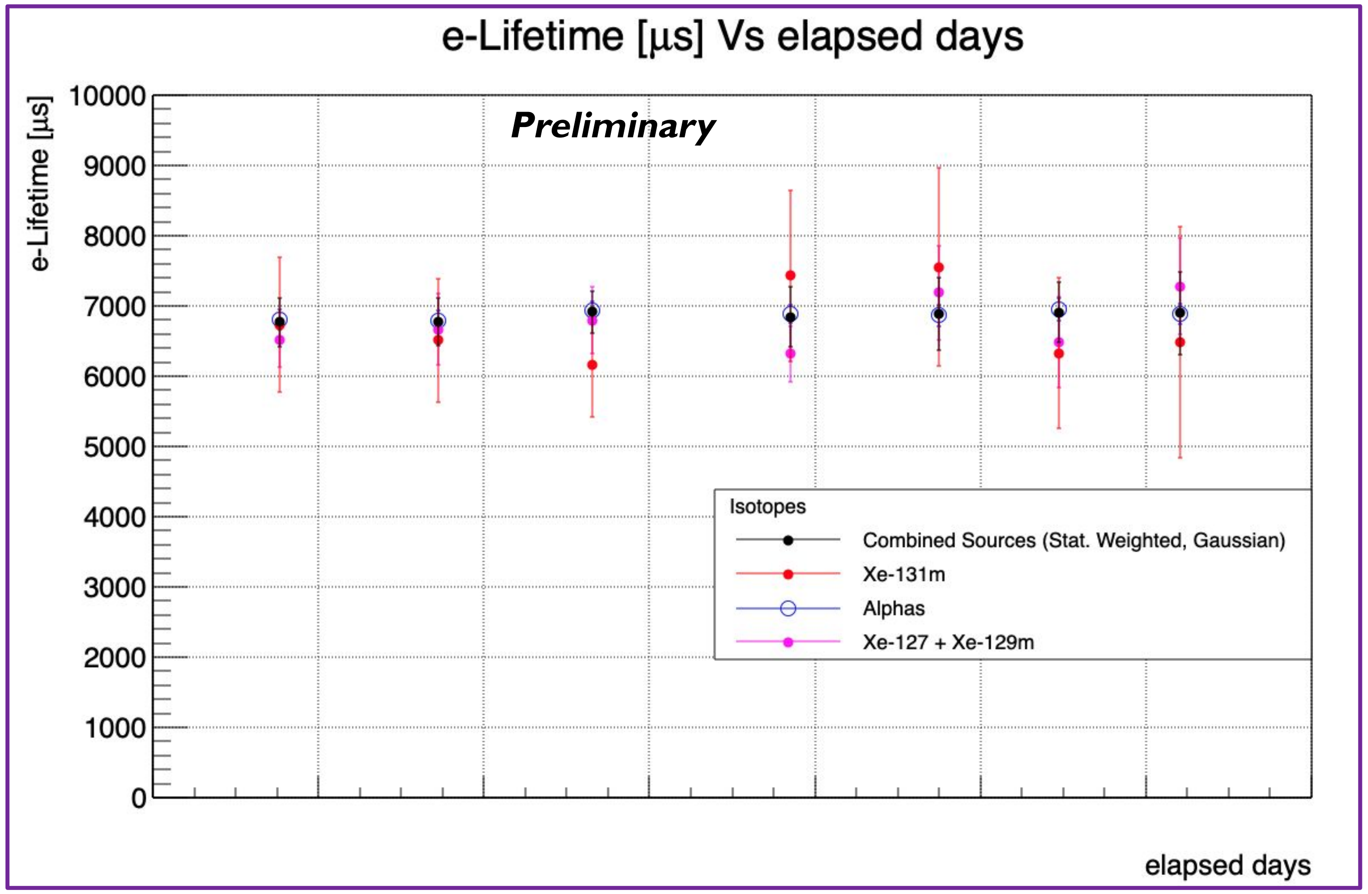
Calibrating with High Energy Backgrounds

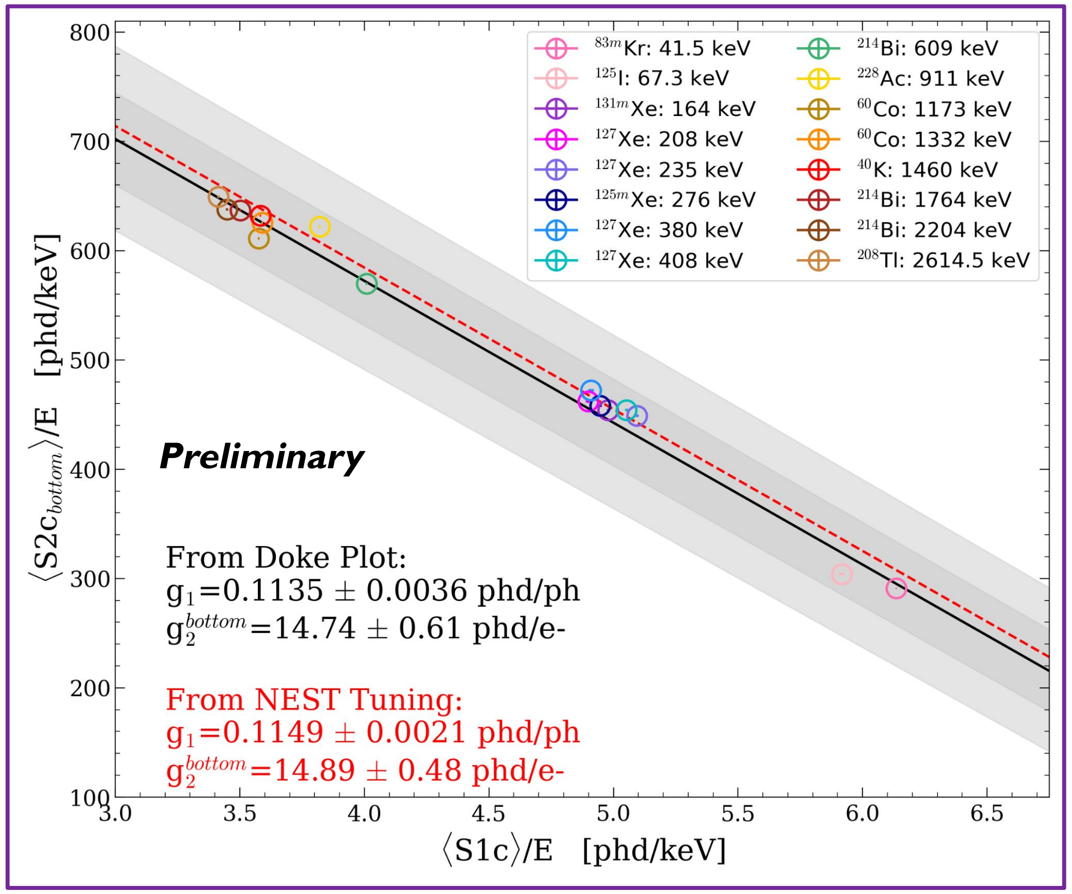
Internal mono-energetic sources provide electron lifetime (purity) and a cross-check on g_1,g_2

- **Electron Lifetime**:
  - Characterized with S2 size as a function of depth for ^{131m}Xe, ^{127}Xe, injected ^{83m}Kr, and MeV-scale alphas
  - Has varied between 5000 and 8000 μs during science run (Original Goal: 850 μs)
  - 951 μs TPC depth (1.54 mm/μs average drift speed)
- **Doke Plot:**
  - Measuring g_1 and g_2 from mono-energetic background and calibration sources
    - Using bottom PMT g_2 here; linearly related to the full TPC g_2
  - Results are in agreement with the results from NEST tuning with tritium and D-D

$$E = W\left(\frac{S1c}{g_1} + \frac{S2c}{g_2}\right)$$

$$\frac{S2c}{E} = \frac{g_2}{W} - \left(\frac{g_2}{g_1}\right)\frac{S1c}{E}$$





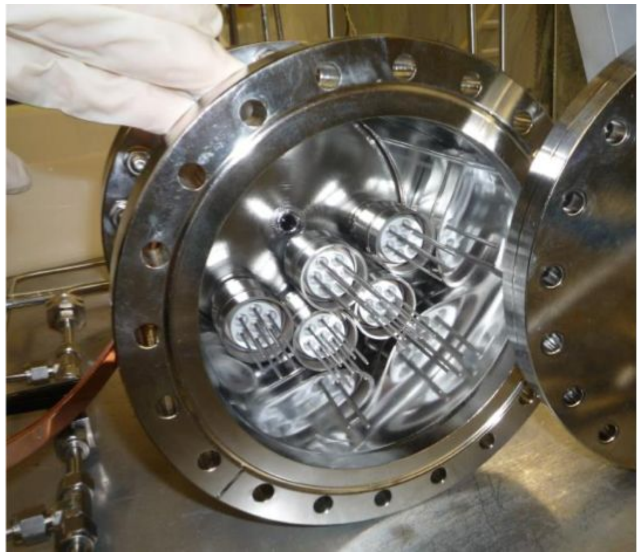
The LUX-ZEPLIN (LZ) radioactivity and cleanliness control programs
LZ Collaboration, D.S. Akerib et al. (Jun 3, 2020) Published in: *Eur.Phys.J.C* 80 (2020) 11, 1044 e-Print: 2006.02506

Background Sources and Mitigation

- Detector materials
  - Nothing went into the detector without screening
  - Radio-assay campaign & neutron activation analysis
- Rn emanation
  - Four screening sites
  - All major parts emanated before assembly
- Rn daughters and dust on surfaces
  - TPC assembly in Rn-reduced cleanroom
  - Dust <500 ng/cm^2 on all LXe wetted surfaces
  - Rn-daughter plate-out on TPC walls <0.5 mBq/m^2
- Xenon contaminants — ^{85}Kr, ^{39}Ar
  - Charcoal chromatography at SLAC
- Cosmogenics and externals
  - 4300 m.w.e. underground at SURF in Lead, SD
  - Instrumented Xe skin region
  - Gd-LS outer detector
  - High purity water shield

Many sources of BG

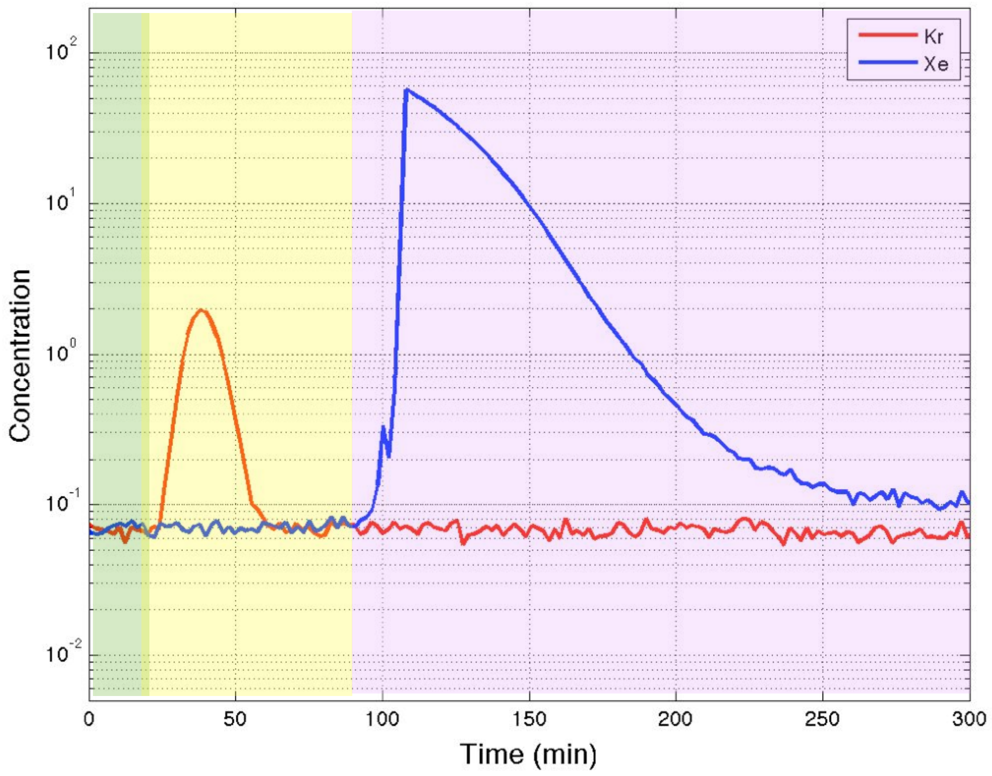
Many methods for BG mitigation

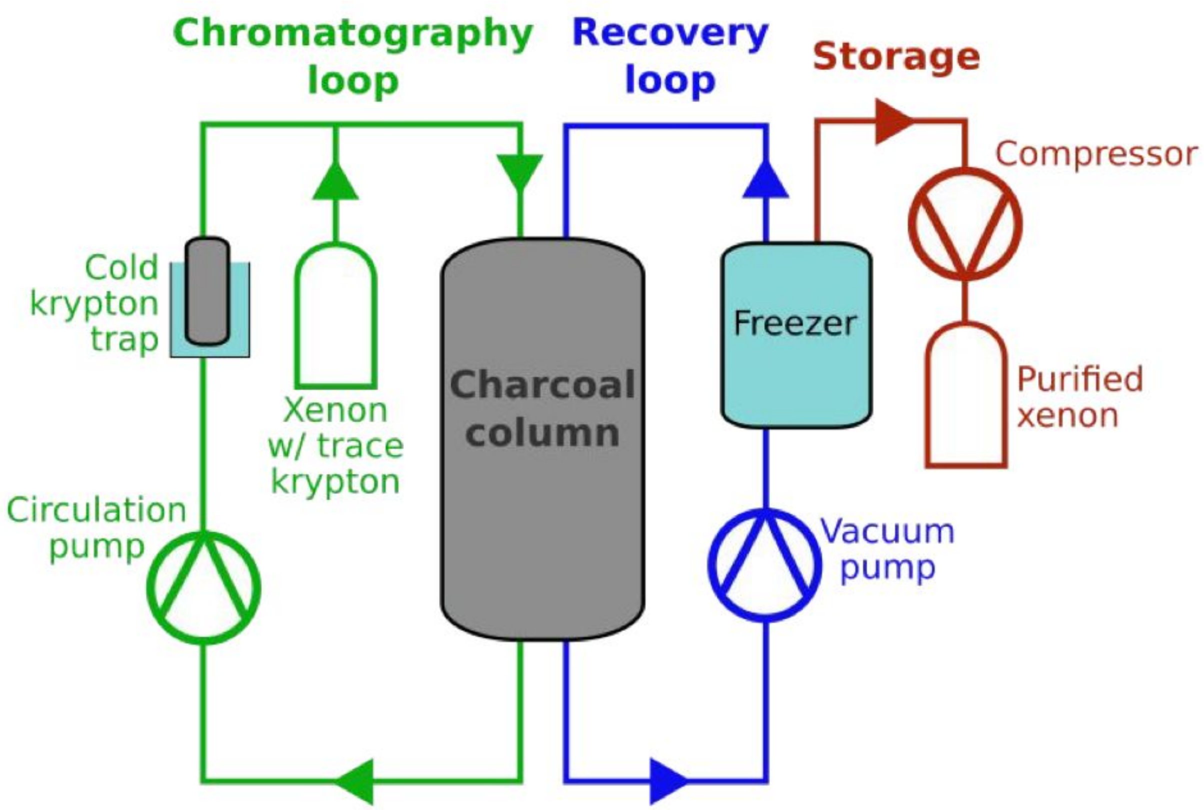


Eur. Phys. J. C, 80: 1044 (2020)

Kr Removal System

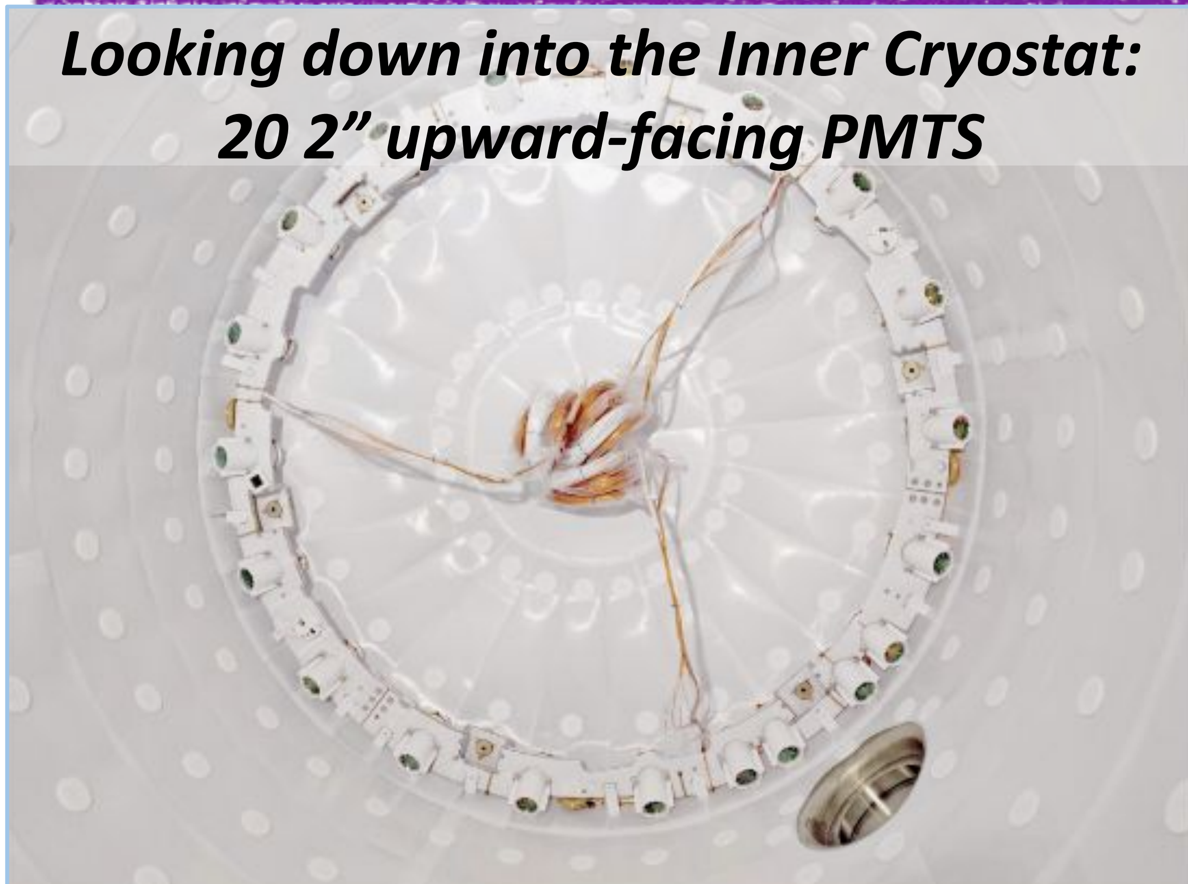
- Gas chromatography to remove Kr from Xe
  - ^{nat}Kr can be reduced to 0.1 ppt g/g ^{nat}Kr/Xe and ^{nat}Ar to a negligible level

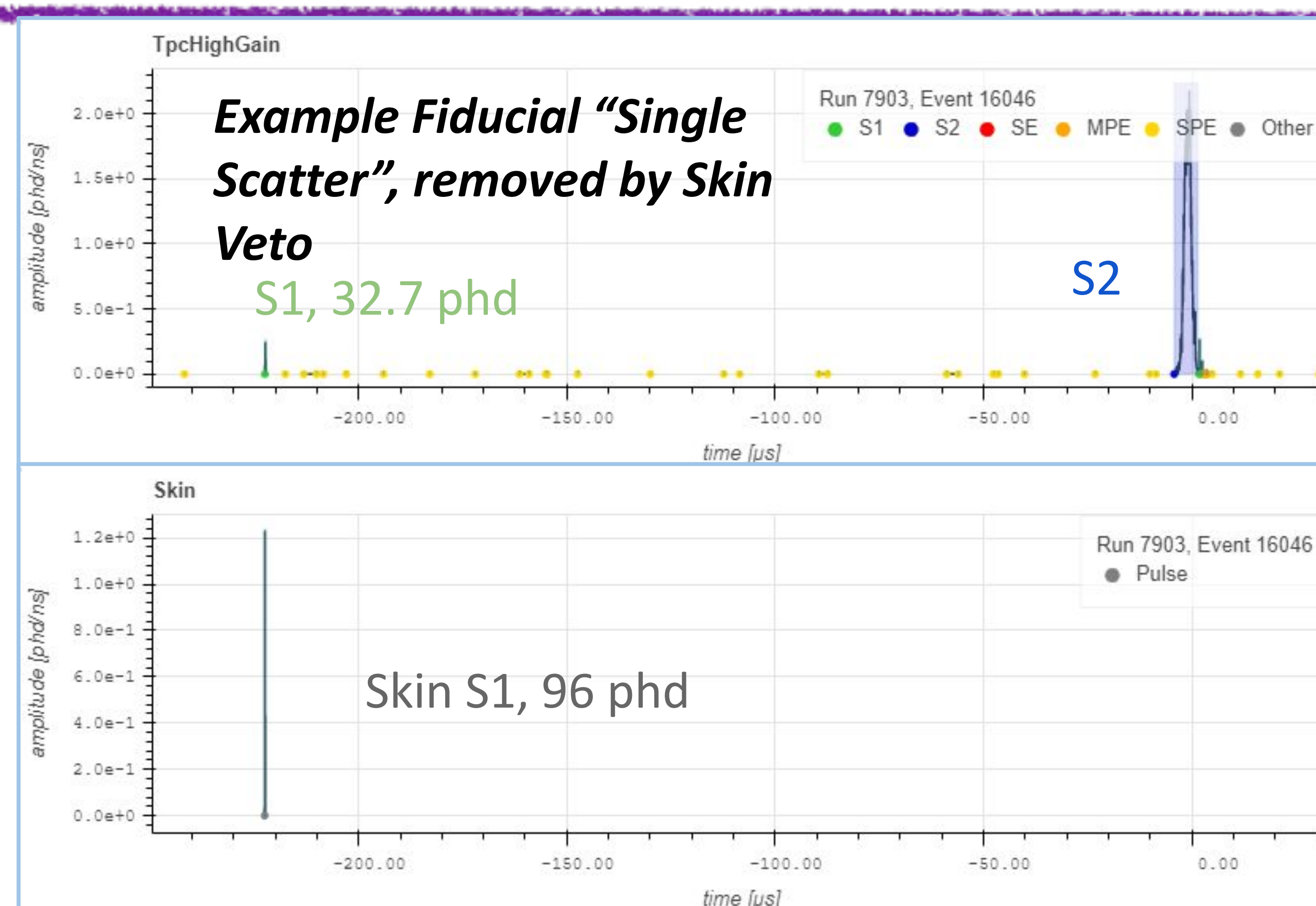


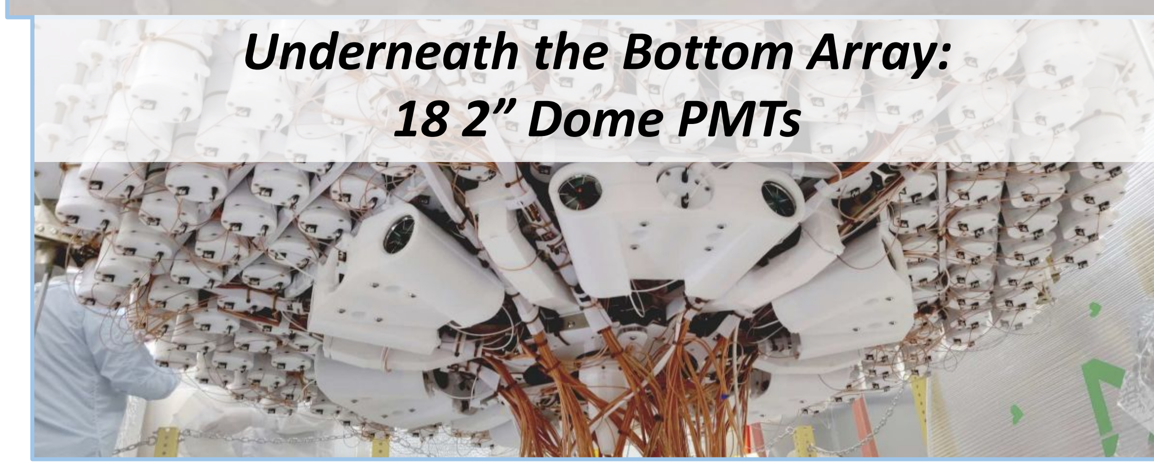


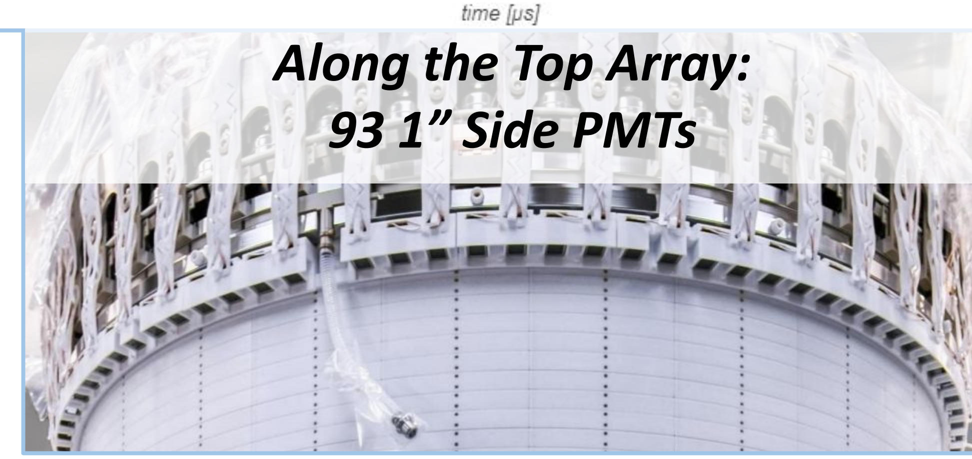
Xenon Skin Veto System

Tagging γs as they enter or leave the TPC



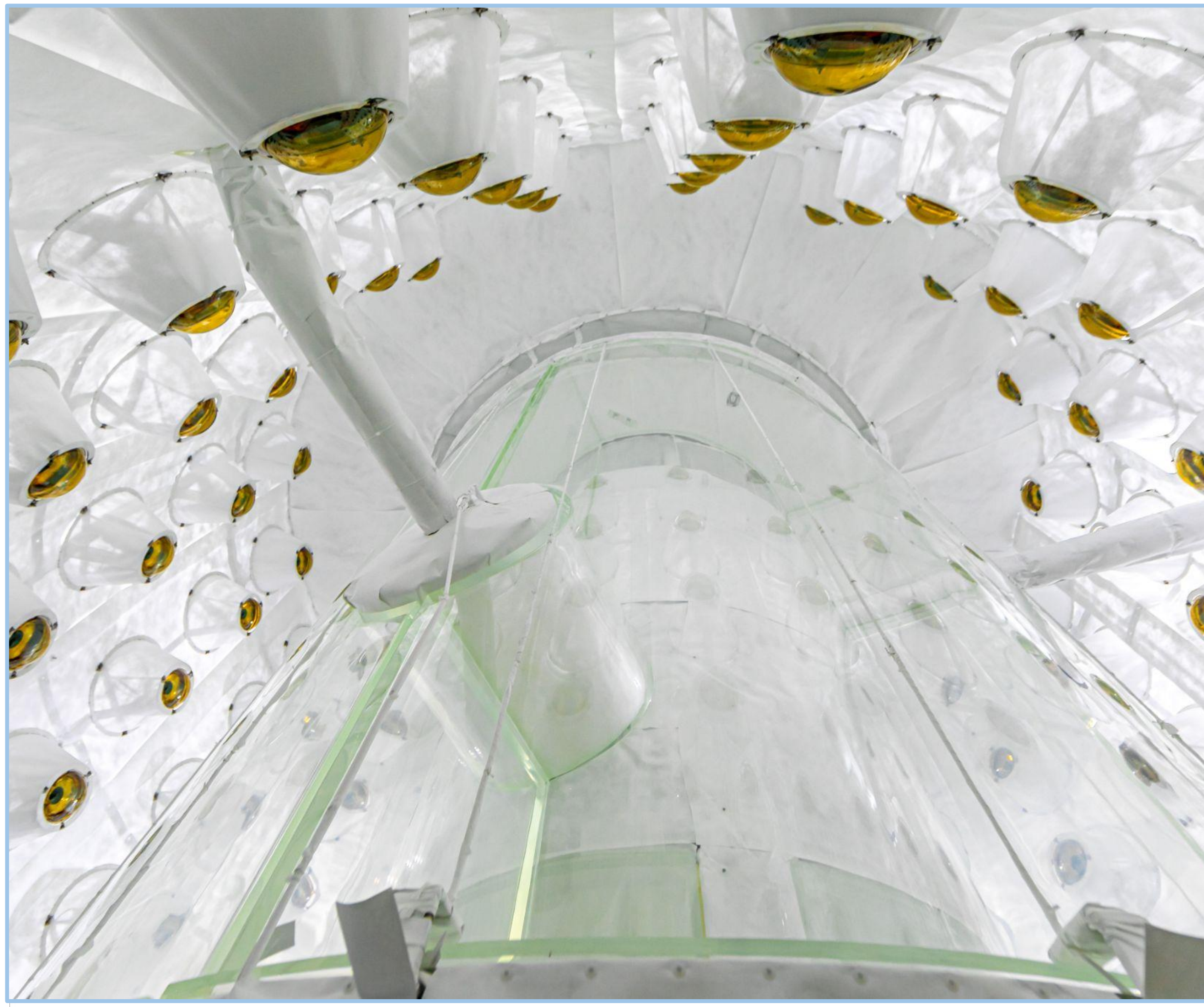




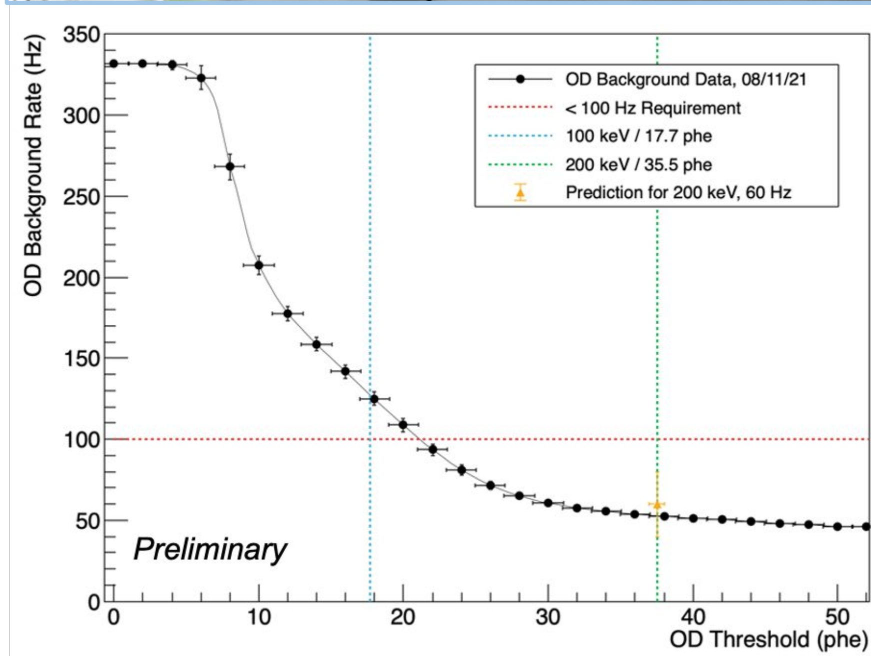


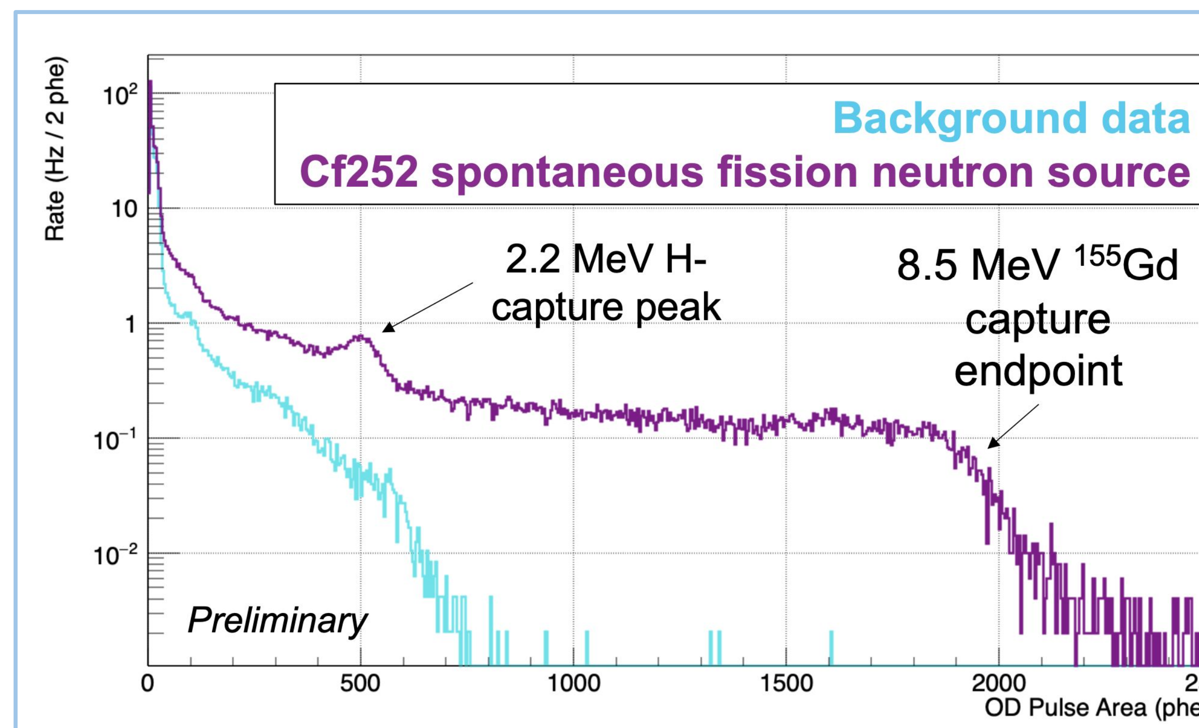
- 4-8 cm of LXe between the TPC and inner cryostat
- γ tagging efficiency of 78 ± 5% based on ^{127}Xe decays originating in the TPC

The Outer Detector (OD)

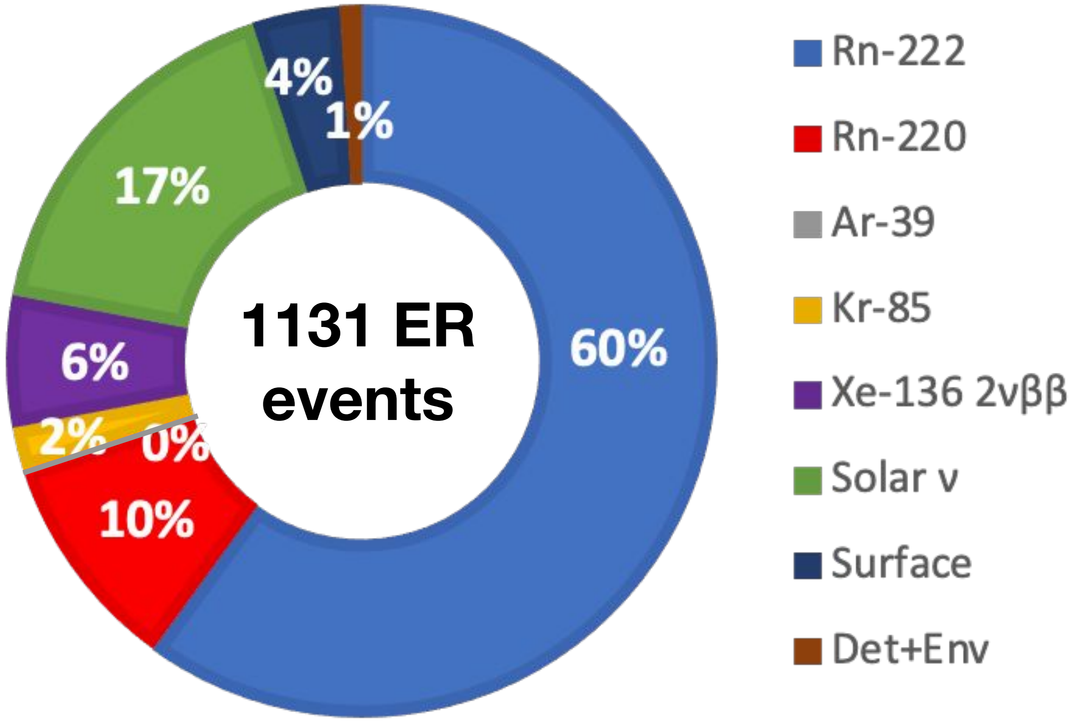


- Ensemble of six acrylic tanks filled with 17 tonnes of Gd-loaded liquid scintillator
- 120 8” PMTs mounted to the water tank
- TPC Single Scatter NR tagging-efficiency: 88.4% (from calibration with AmLi)
- Observed slightly lower backgrounds than expected
  - Leads to threshold below 200 keV

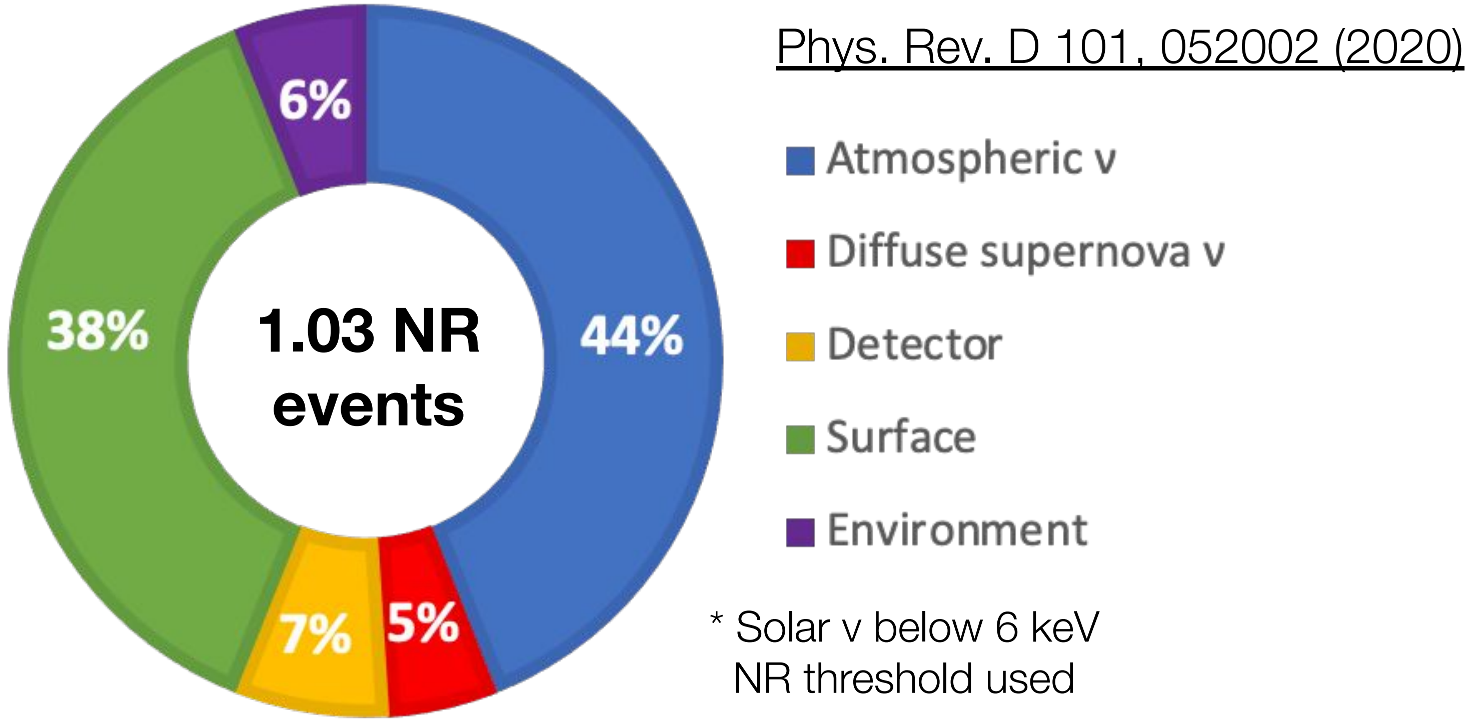




Expected backgrounds for 5.6 t fiducial - 1000 days



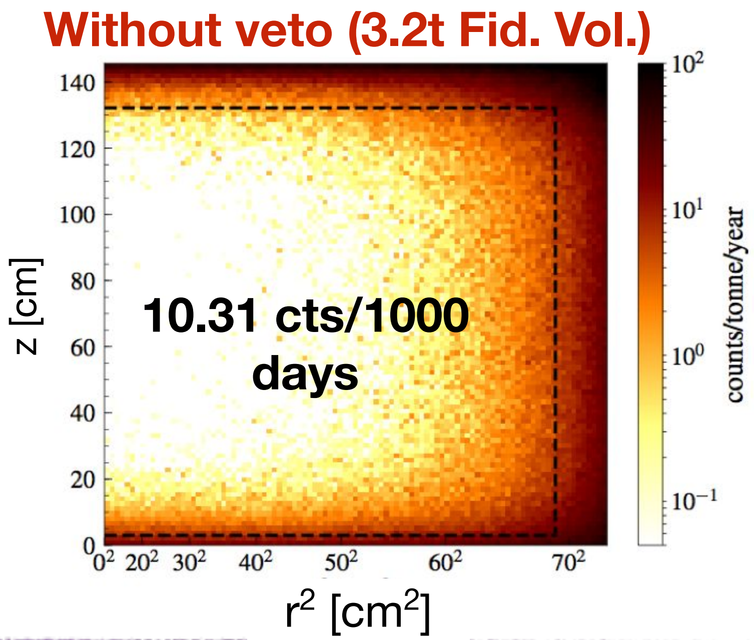
5.66 events after
99.5% ER discrimination



* Solar ν below 6 keV NR threshold used

0.52 events after
50% NR acceptance

Distributions of single-scatter nuclear recoils in 40 Gev WIMP ROI (6-30 keV) →



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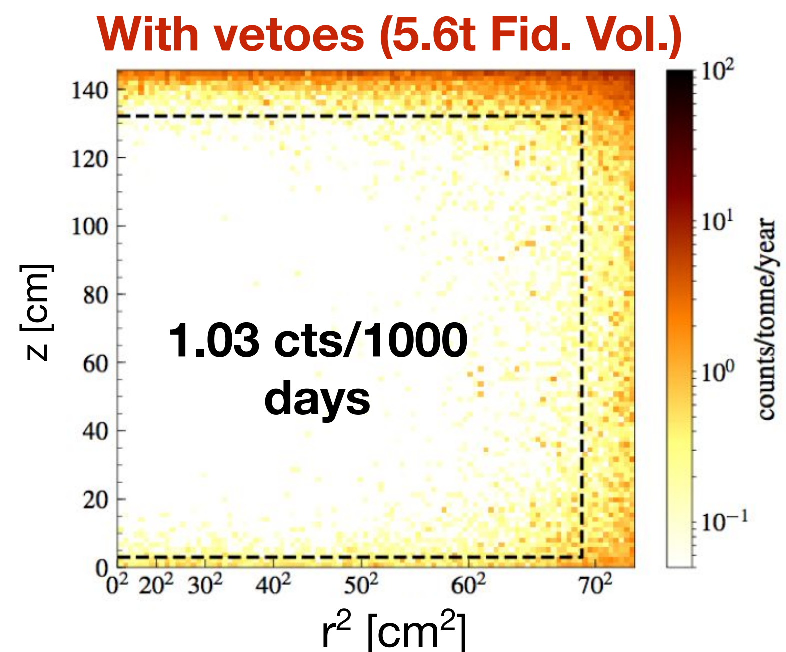
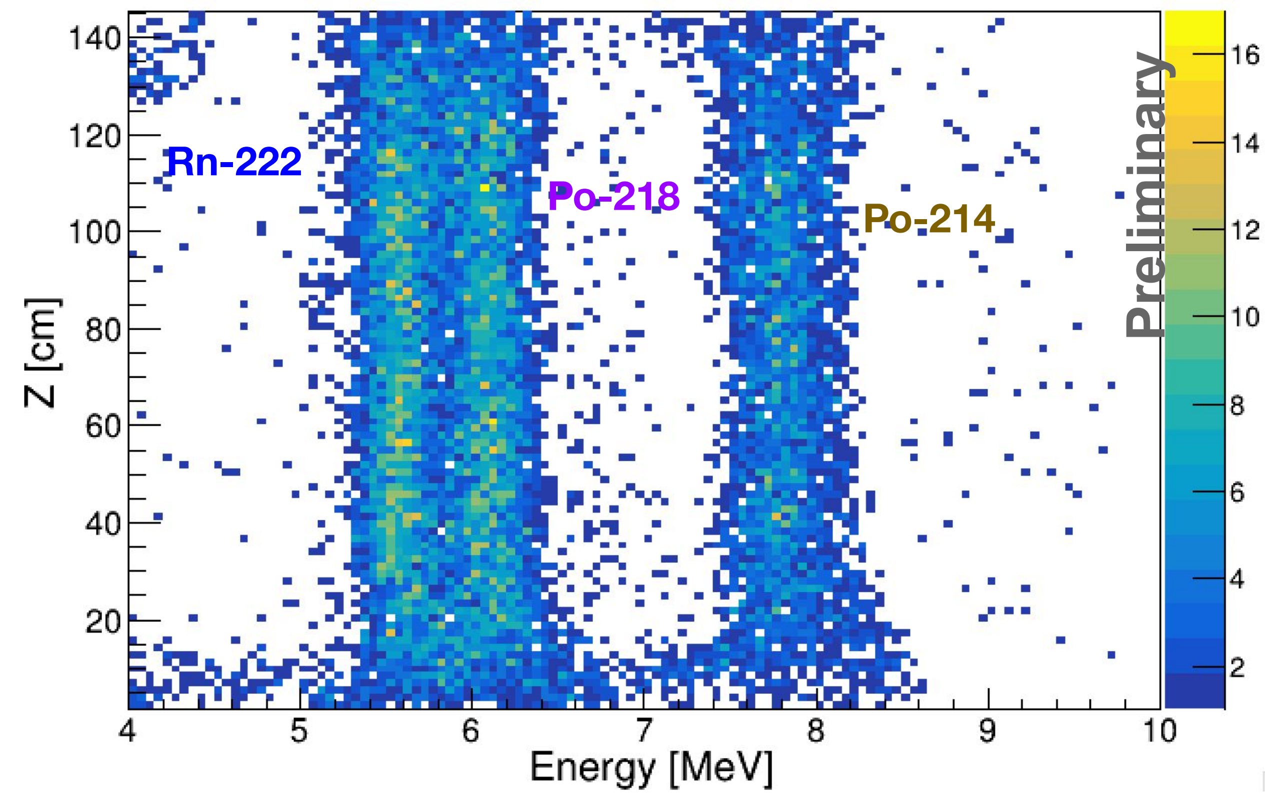
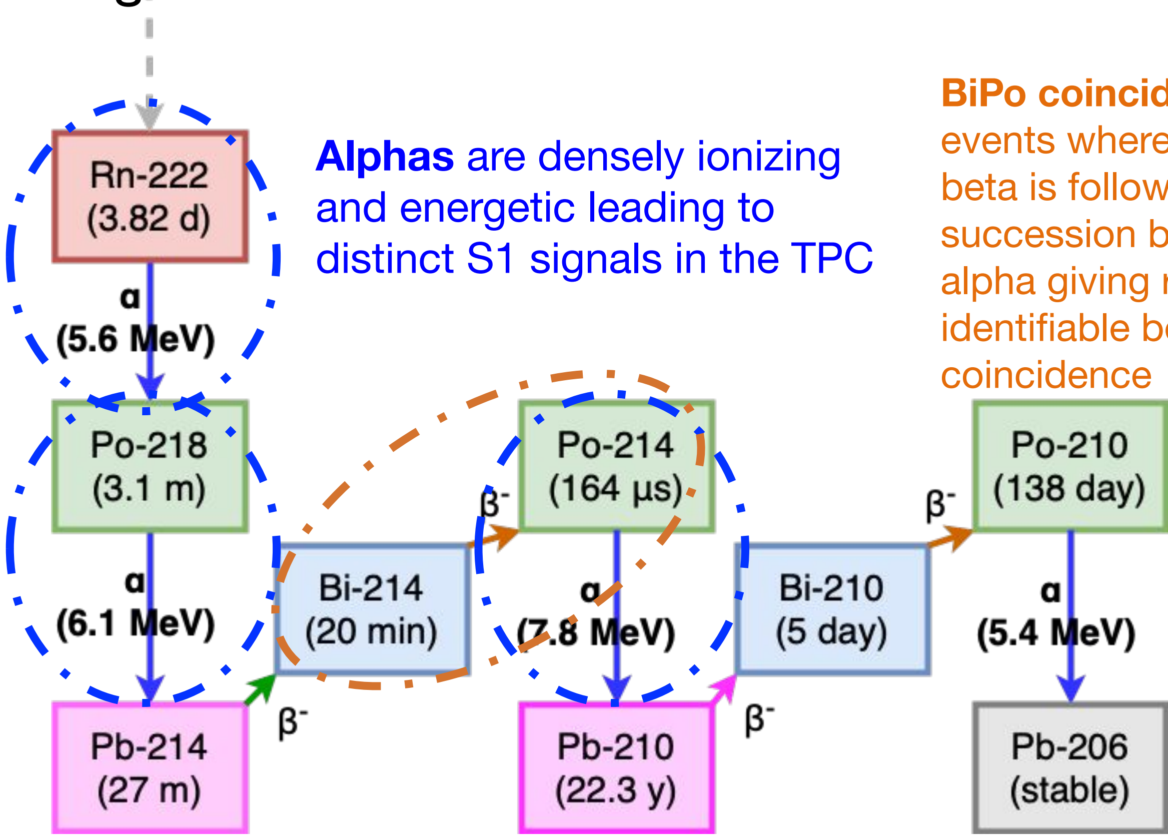


Backgrounds Analysis: Rn chain backgrounds

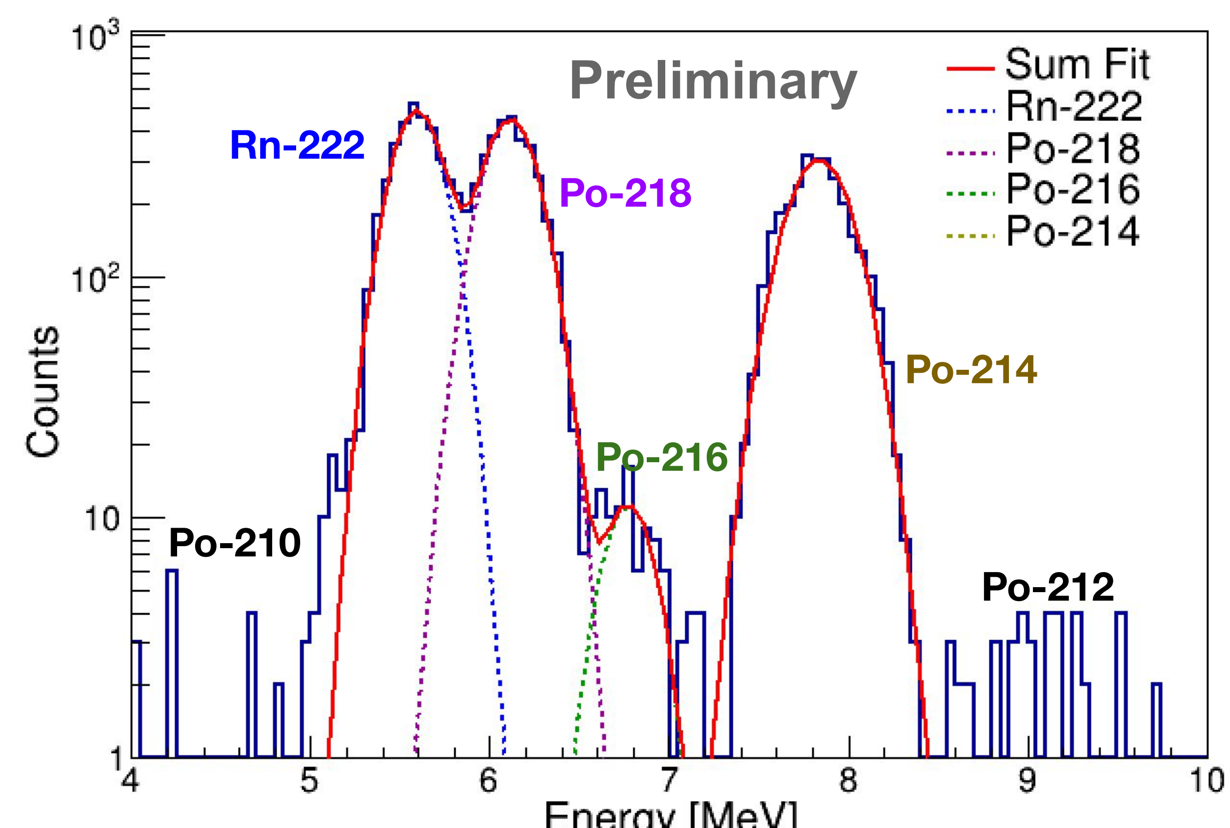
- Rn-222 and Rn-220 emanates from U-238 and Th-232 contamination in detector materials and diffuses into the Xenon
  - Inline radon reduction system further reduces radon concentration
- The "naked betas" from Pb-214/ Pb-212 are a WIMP background
  - Pb-214 is the largest background contribution
- Preliminary analysis shows Rn-222 rate within expected range





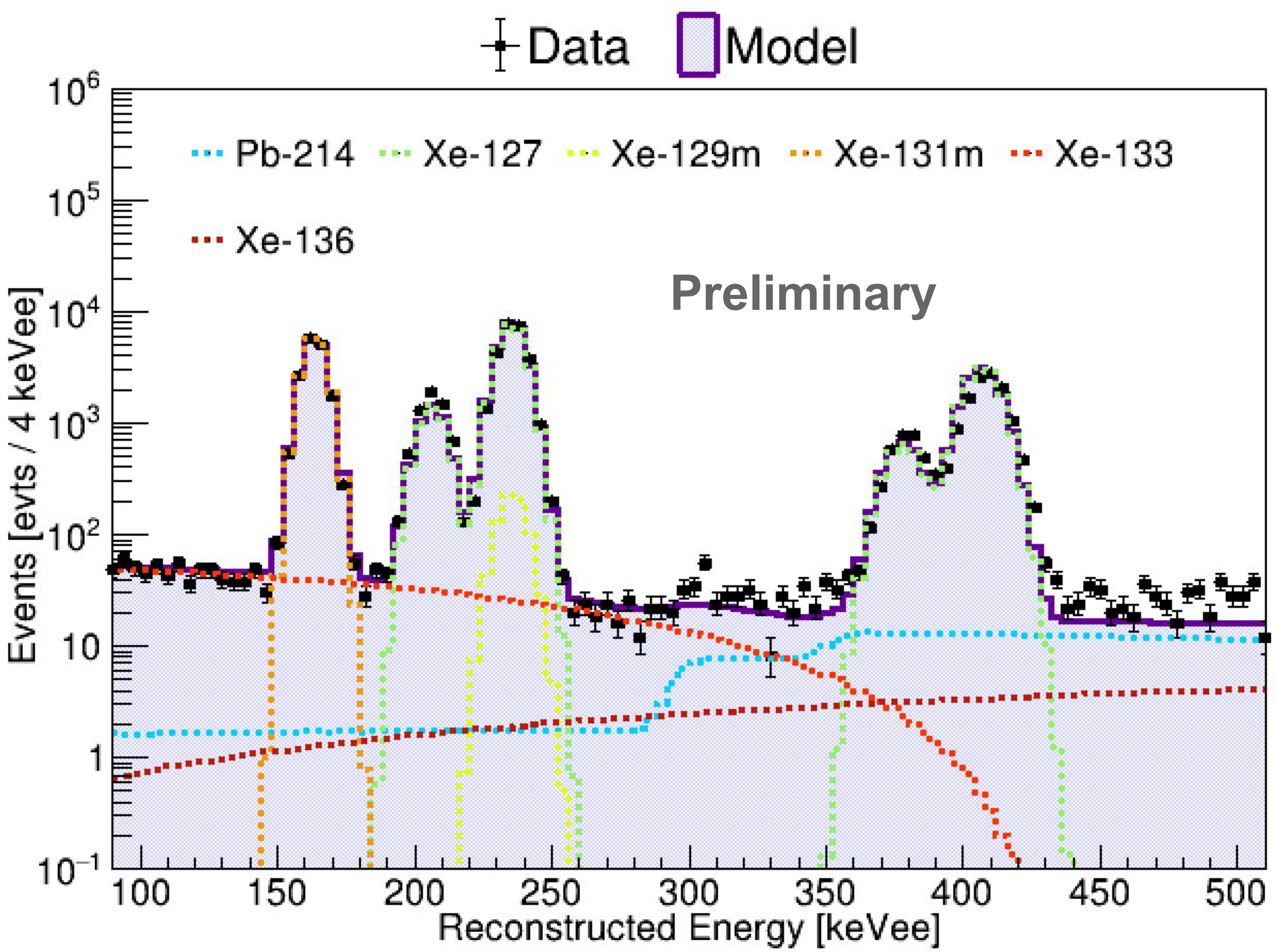
Alphas are densely ionizing and energetic leading to distinct S1 signals in the TPC

BiPo coincidences are events where the Bi-214 beta is followed in quick succession by a Po-214 alpha giving rise to an identifiable beta-alpha coincidence

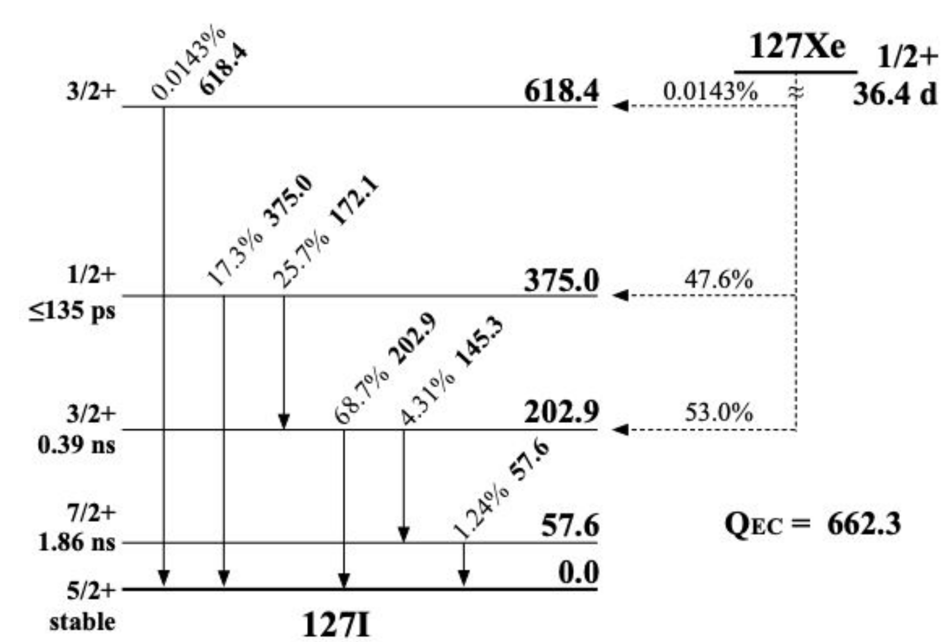


Constraining Xenon Activation Backgrounds

- Xenon can become activated by cosmogenics leading to background contributions from ^{127}Xe, ^{129m}Xe, ^{131m}Xe, ^{133}Xe (other Xe activation products are much shorter lived)
  - ^{127}Xe can contribute to low energy ER backgrounds
- Activation rates can be estimated via extrapolations from LUX results and Activia calculations (open-source package for estimating activation)

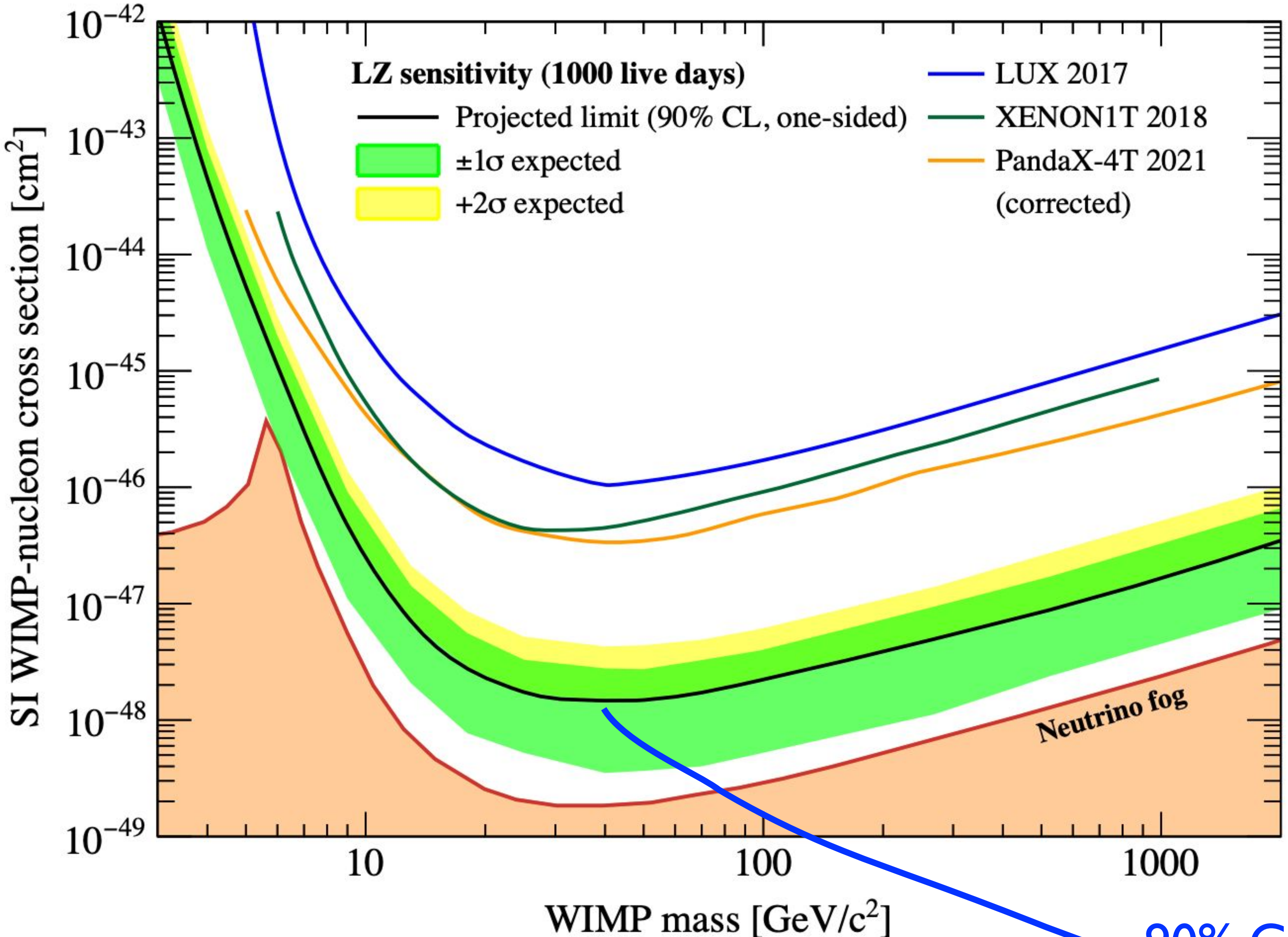


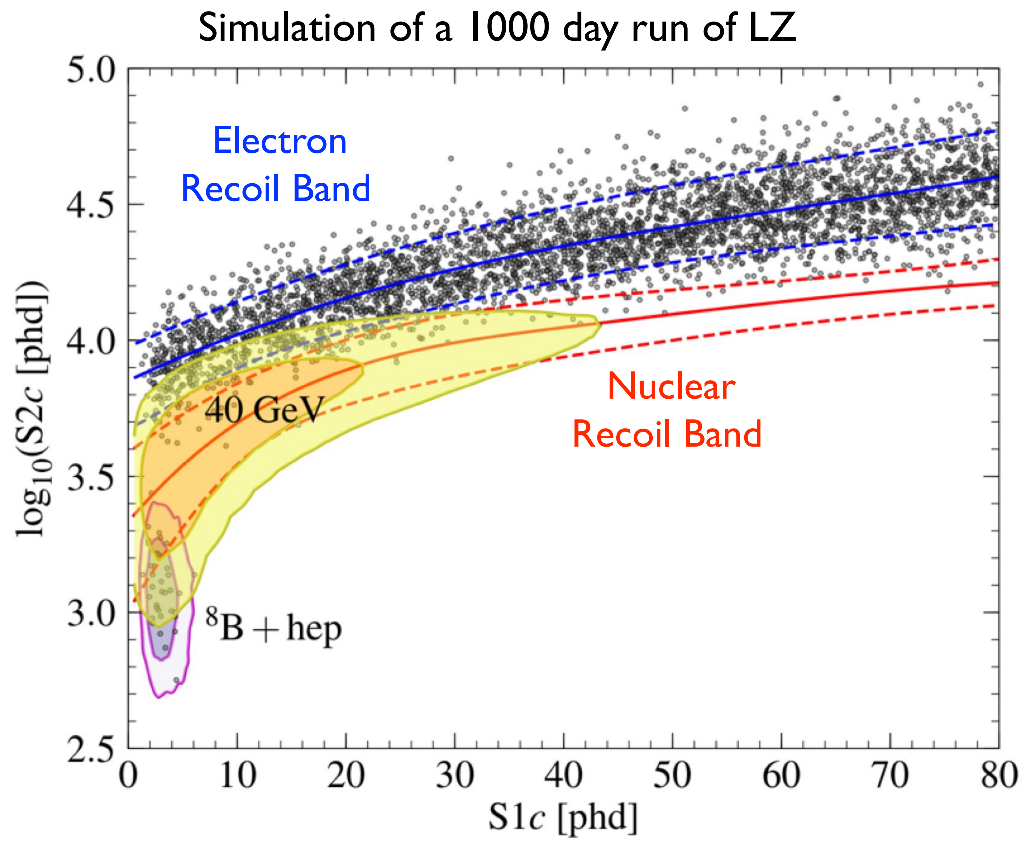
Xe-127 decays by electron capture



WIMP background arises from rare case where Xe-127 gamma escapes the TPC and low energy cascade occurs within bulk
⇒ Highly veto suppressed and strong positional dependence

Projected Sensitivity (5.6 t exposure, 1000 live days)





90% CL minimum of
1.4×10^{-48} cm^2 at 40 GeV/c^2

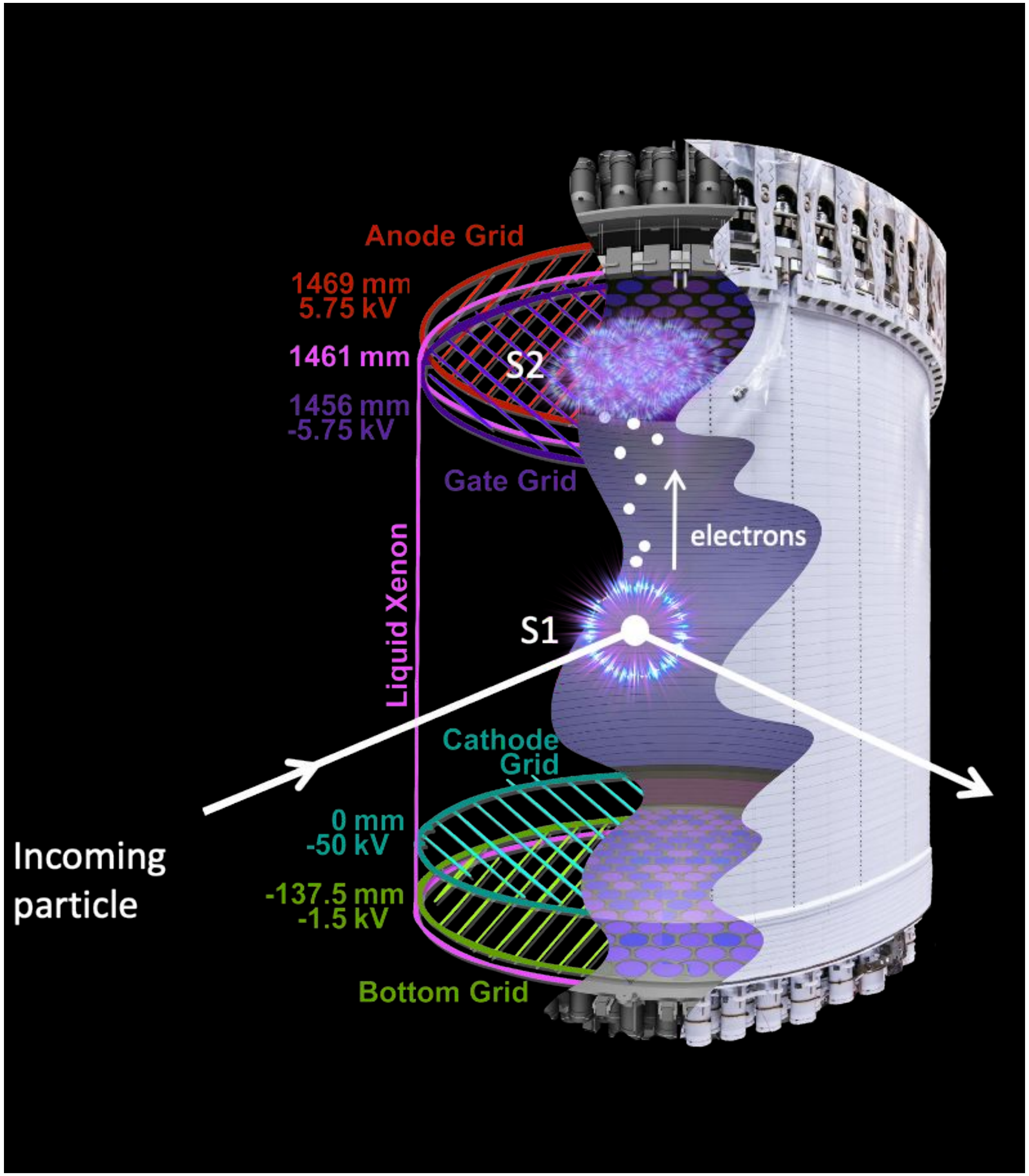
Phys. Rev. D 101, 052002 (2020)

Outlook

- LZ is a multi-physics experiment, primed for detection of WIMPs
- Construction and Commissioning was completed successfully, and LZ has been collecting science data
- First Science Results expected this year ***Stay Tuned!***

2022 will be an exciting year for LZ and the Dark Matter Research Community!

Thank You!



Thanks to our sponsors and 35 participating institutions!

U.S. Department of Energy

Office of Science

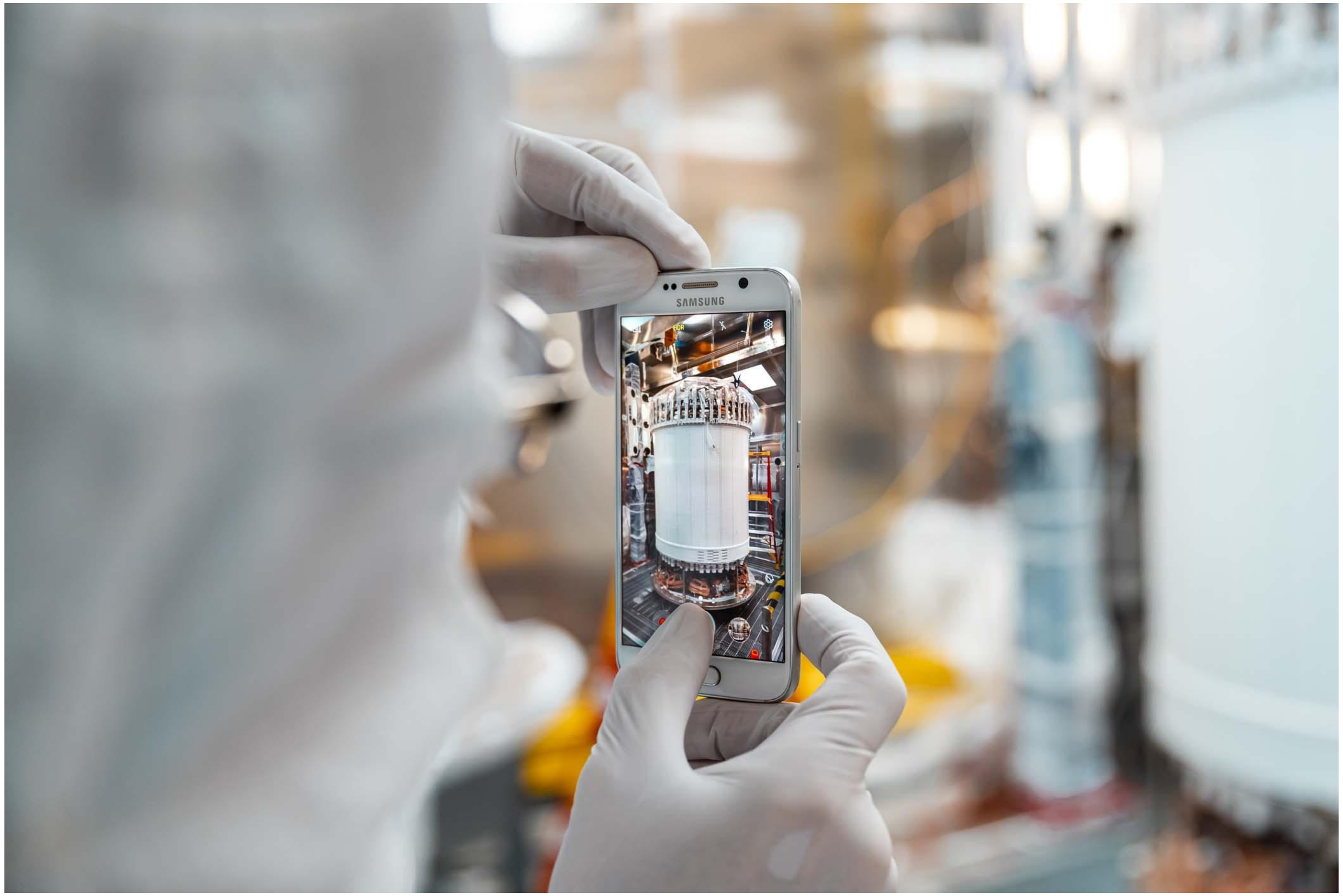
Science and Technology Facilities Council

FCT Fundação para a Ciência e a Tecnologia

Institute for Basic Science

Sanford Underground Research Facility

South Dakota Science and Technology Authority



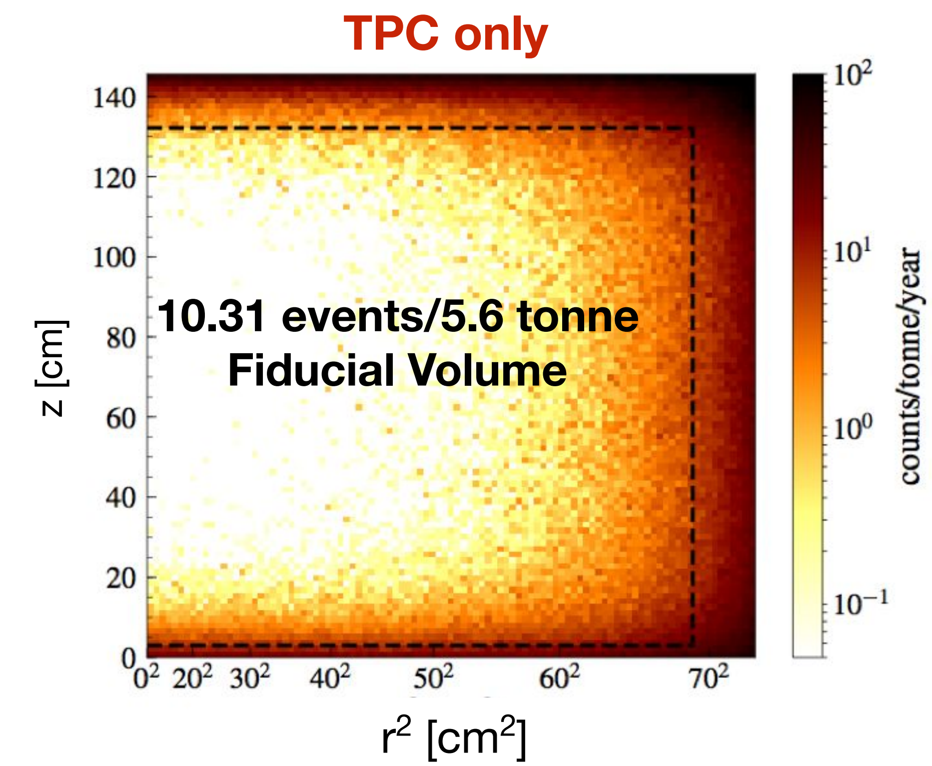
Backup Slides

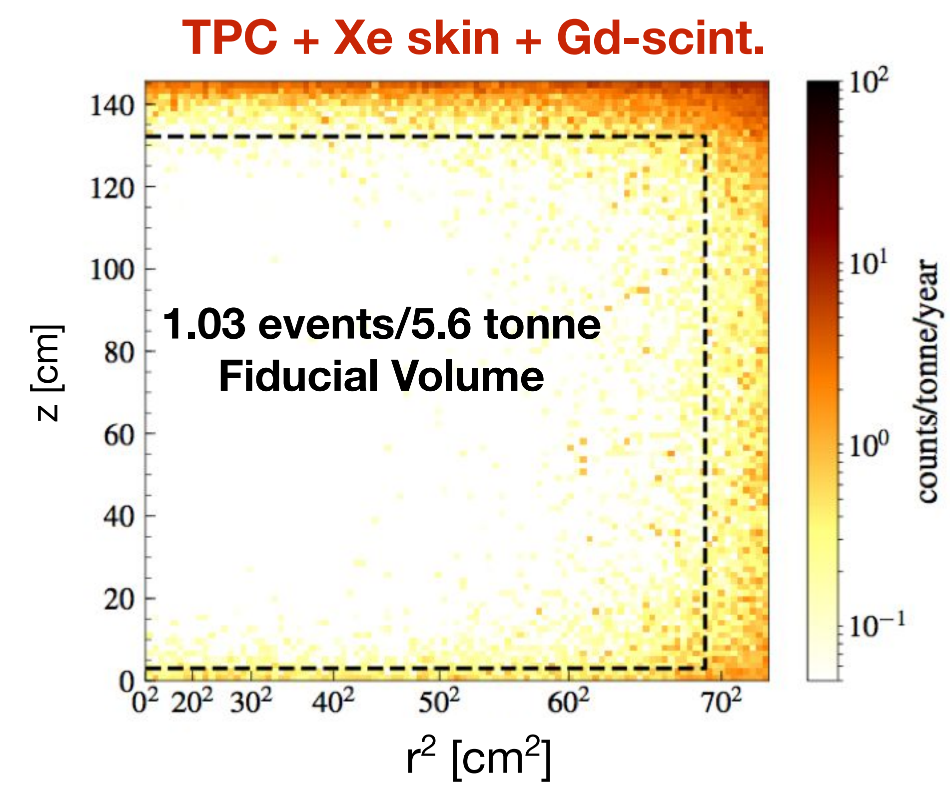
Expected backgrounds for 5.6 t fiducial - 1000 days

Background Source	ER (cts)	NR (cts)
Detector Components	**9**	**0,07**
Surface Contamination	**40**	**0,39**
Laboratory and Cosmogenics	**5**	**0,06**
Xenon Contaminants	**819**	**0**
222Rn	681	0
220Rn	111	0
natKr (0.015 ppt g/g/)	24,5	0
natAr (0.45 pub g/g)	2,5	0
Physics	**258**	**0,51**
136Xe 2νββ	67	0
Solar neutrinos (pp+7Be+13N)	191	0*
Diffuse supernova neutrinos	0	0,05
Atmospheric neutrinos	0	0,46
Total	**1131**	**1,03**
with 99.5% ER discrim., 50% NR eff.	**5,66**	**0,52**

Radon is the dominant background!

* 6 keV NR threshold used

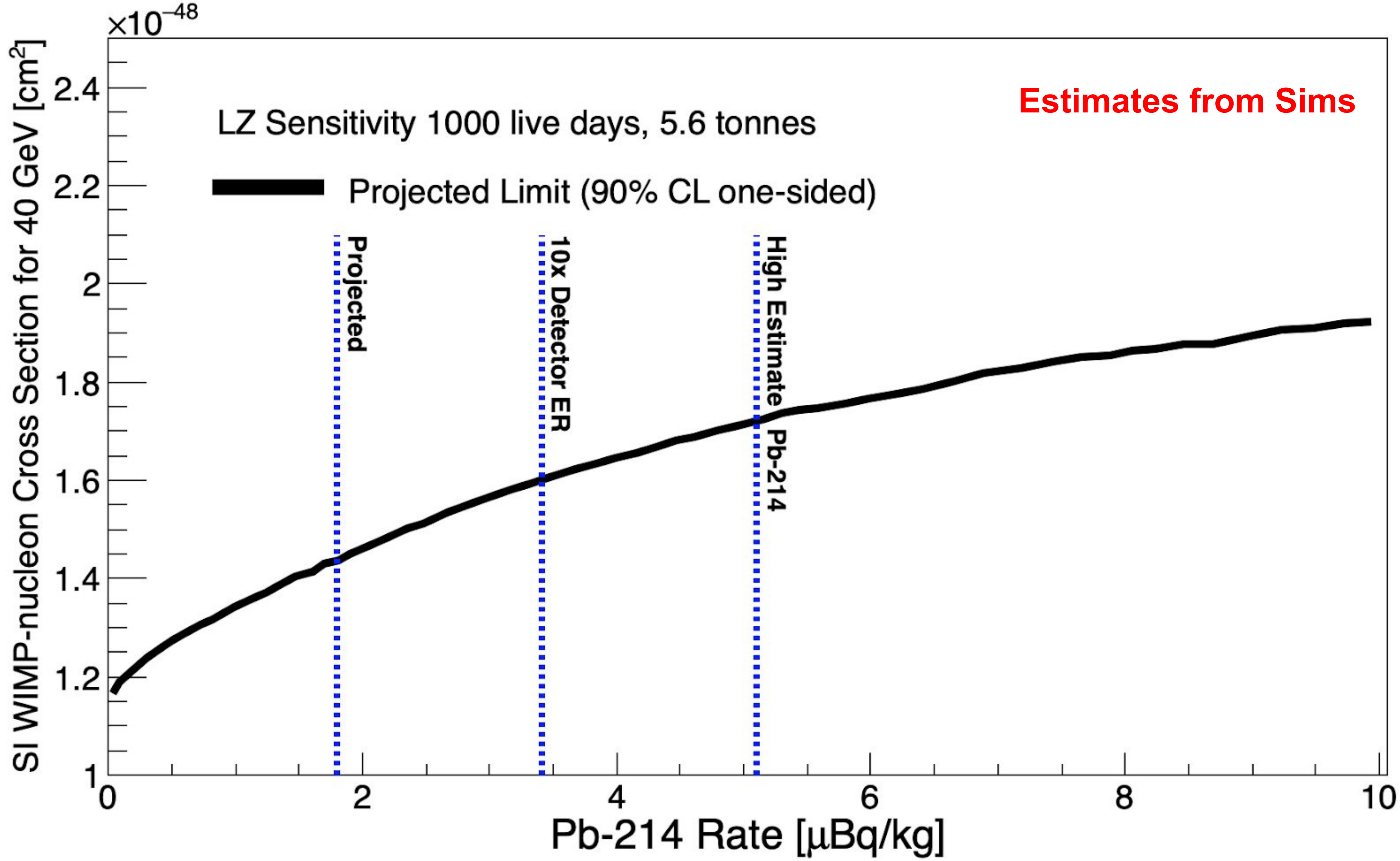




D.S. Akerib et al (LZ collaboration) Phys. Rev. D 101, 052002 (2020)

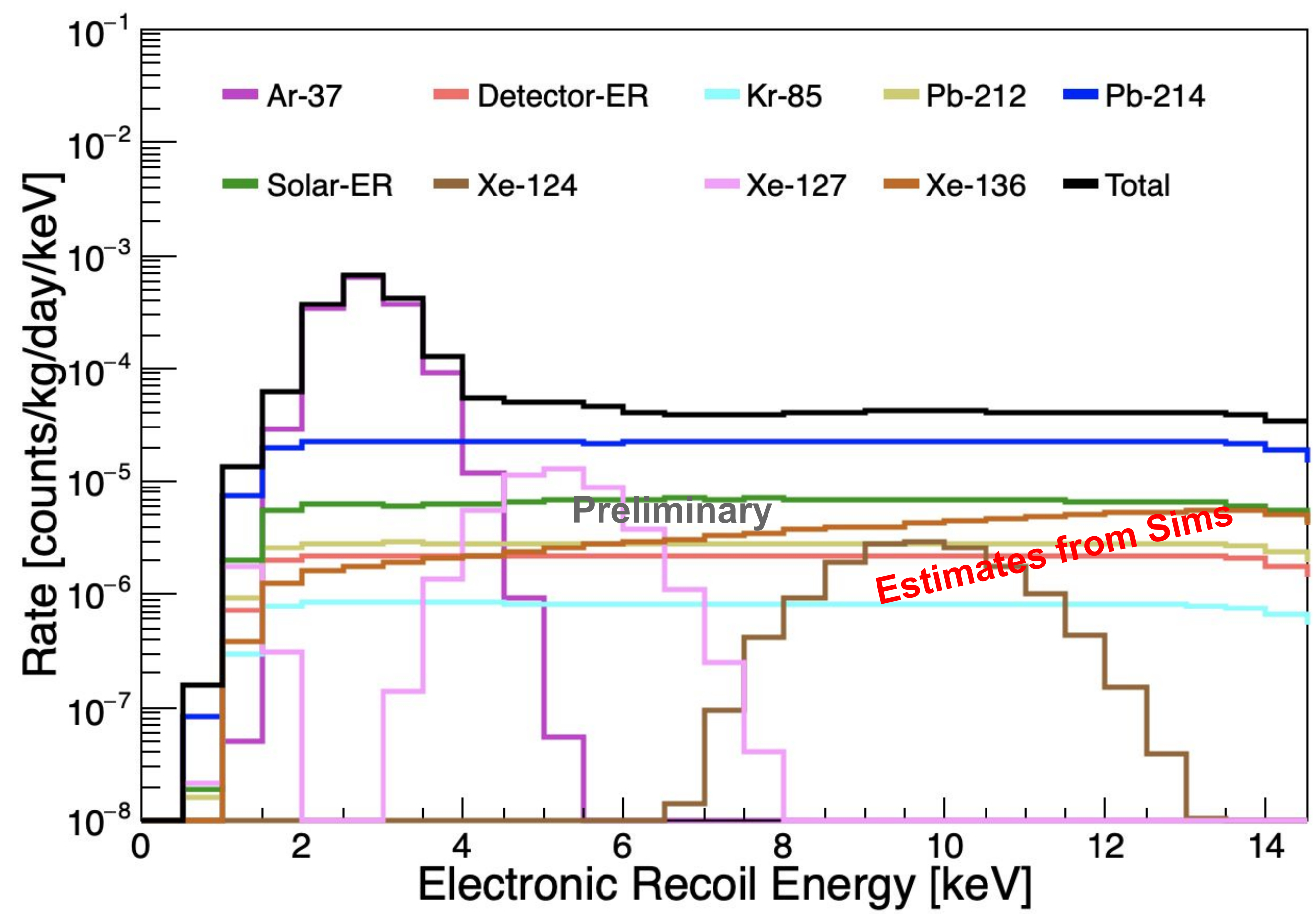
Sensitivity reach vs Pb-214 rate

Impact on 40 GeV WIMP sensitivity with increasing Pb-214 rate, as a proxy for increasing flat ER backgrounds



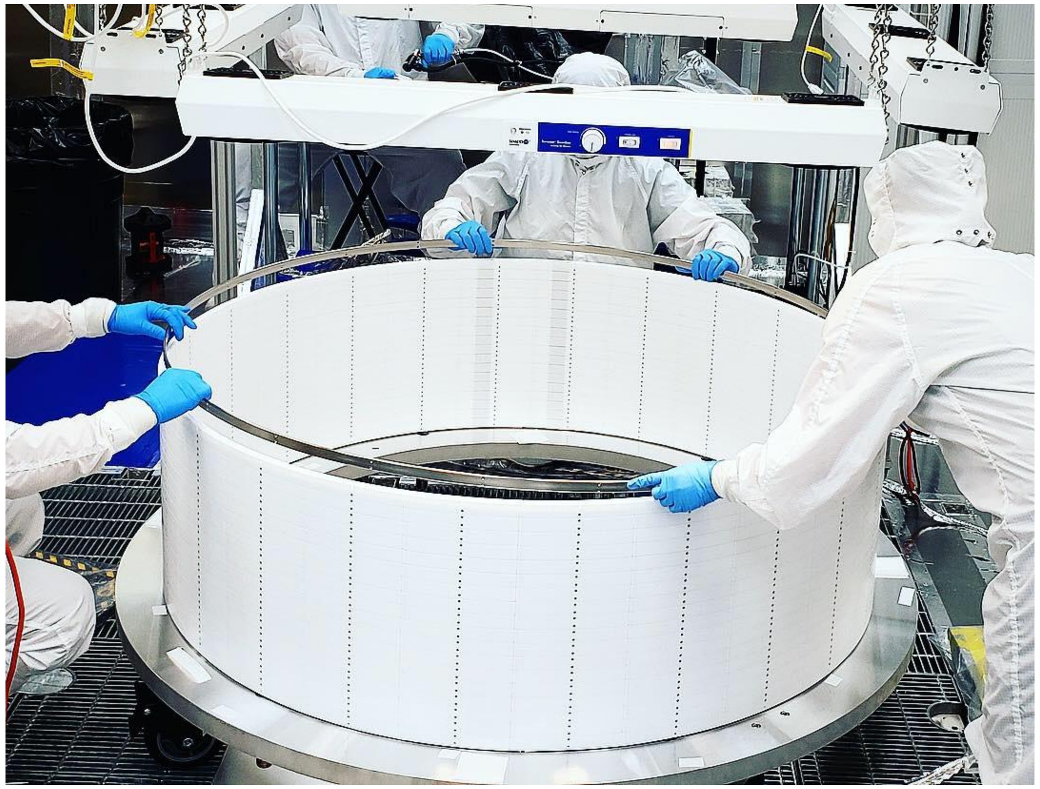
Early Science Backgrounds

- Background model in WIMP ROI is built using tuned background simulations and normalizations derived from the measures described
  - Predicted normalizations using PhysRevD 101.052002
  - * ^{37}Ar extrapolated based on results in arXiv 2201.02858
  - * ^{127}Xe extrapolated using LUX results AstroPart Phys 62, 33

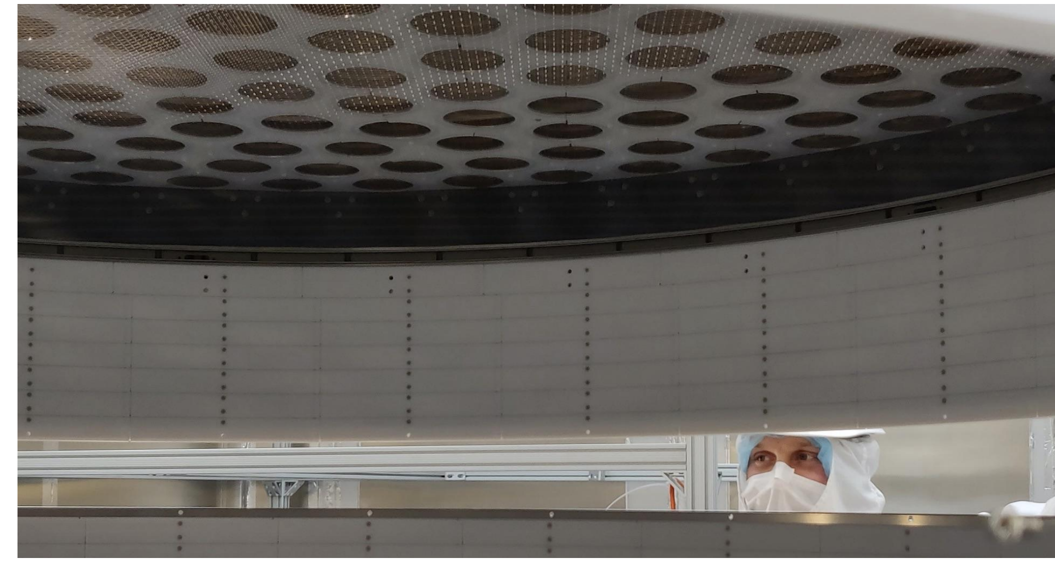


***Ar-37 and Xe-127 have 35 d and 36.4 d half-lives, respectively, and are only backgrounds for early science operations**

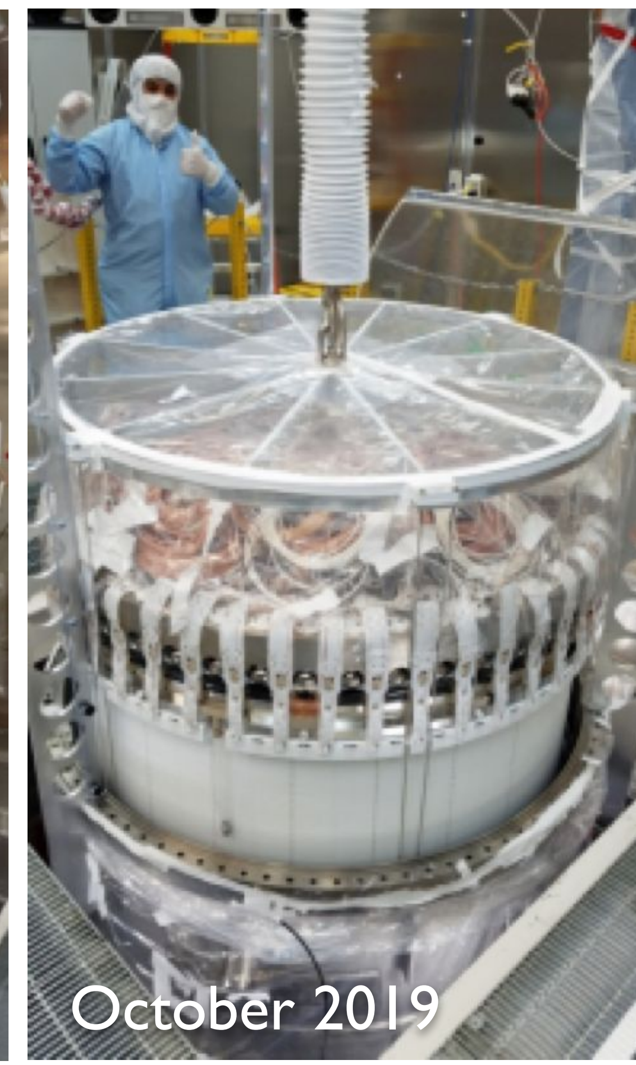
TPC & Skin Integration in the Surface Assembly Lab



Detector integration started in December 2018 at Surface Assembly Laboratory (SURF)
~13,500 working hours

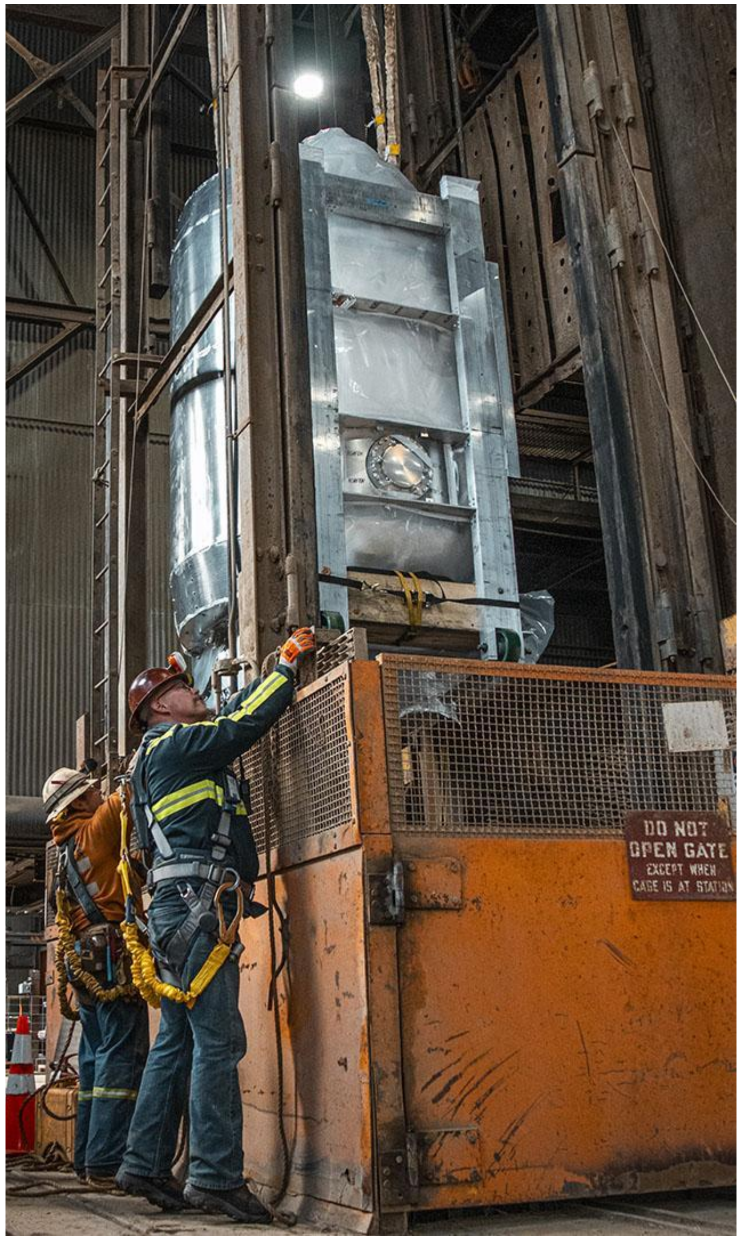


Insertion into inner cryostat vessel



Transport of TPC Underground

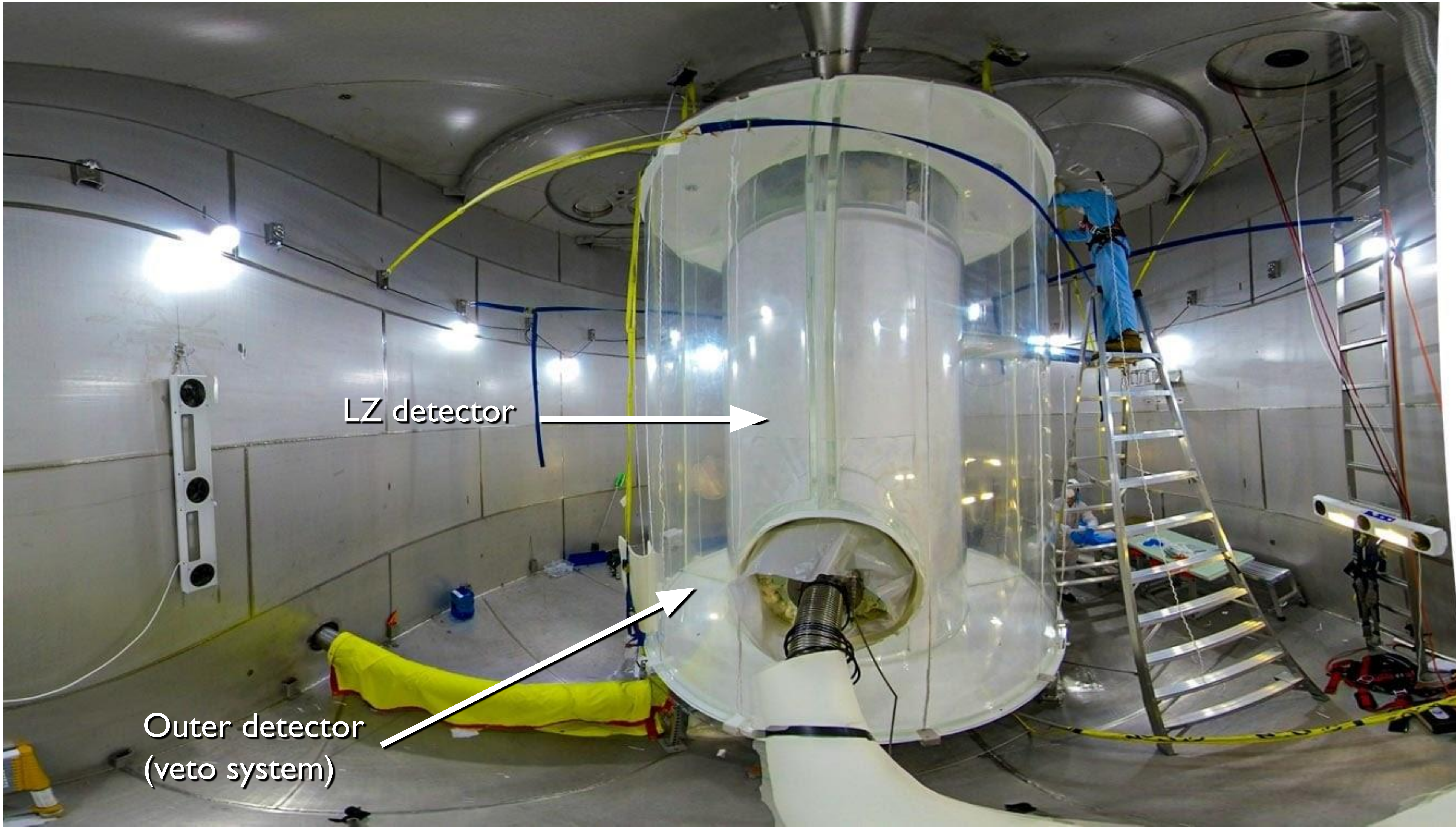
October 2019



Underground deployment I

Making up cathode connections (under N2 purge)

Underground deployment II

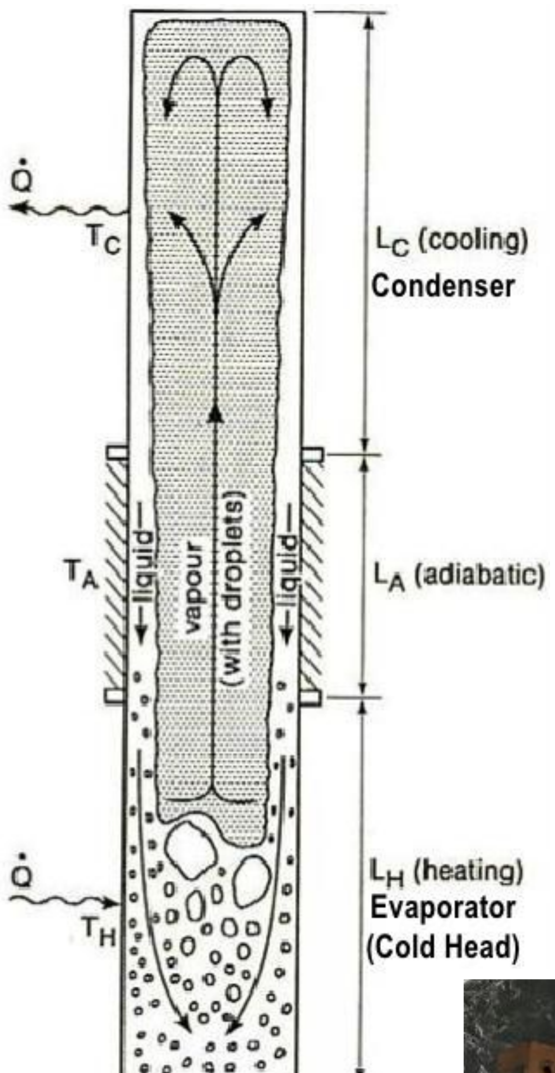


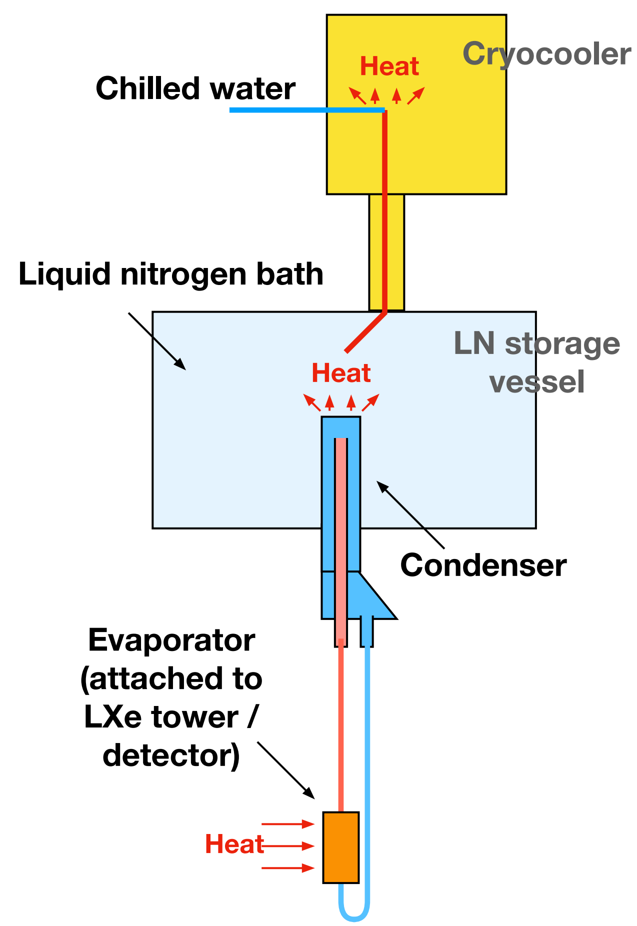
Underground deployment III

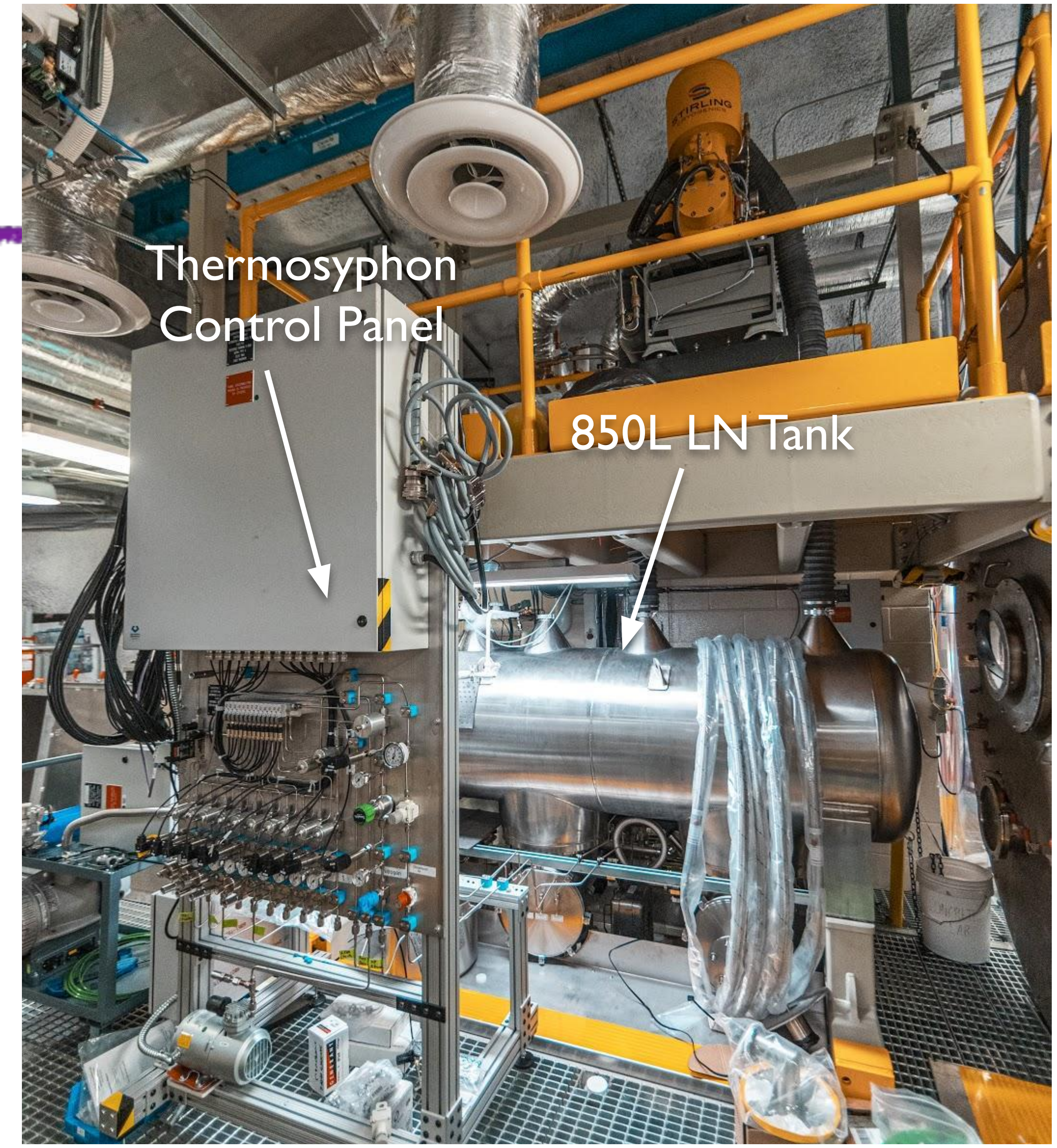
LZ Cryogenics

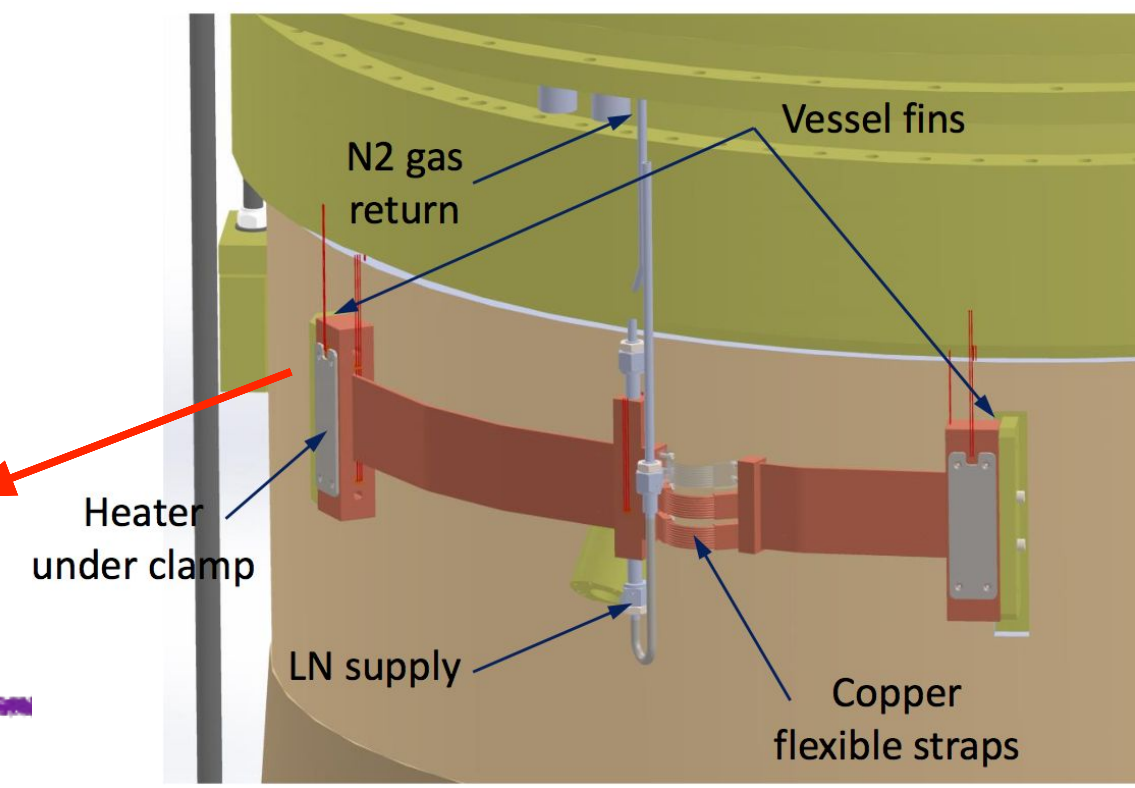
- Cooling provided by thermosyphon technology (also used in LUX)

Thermosyphon principle

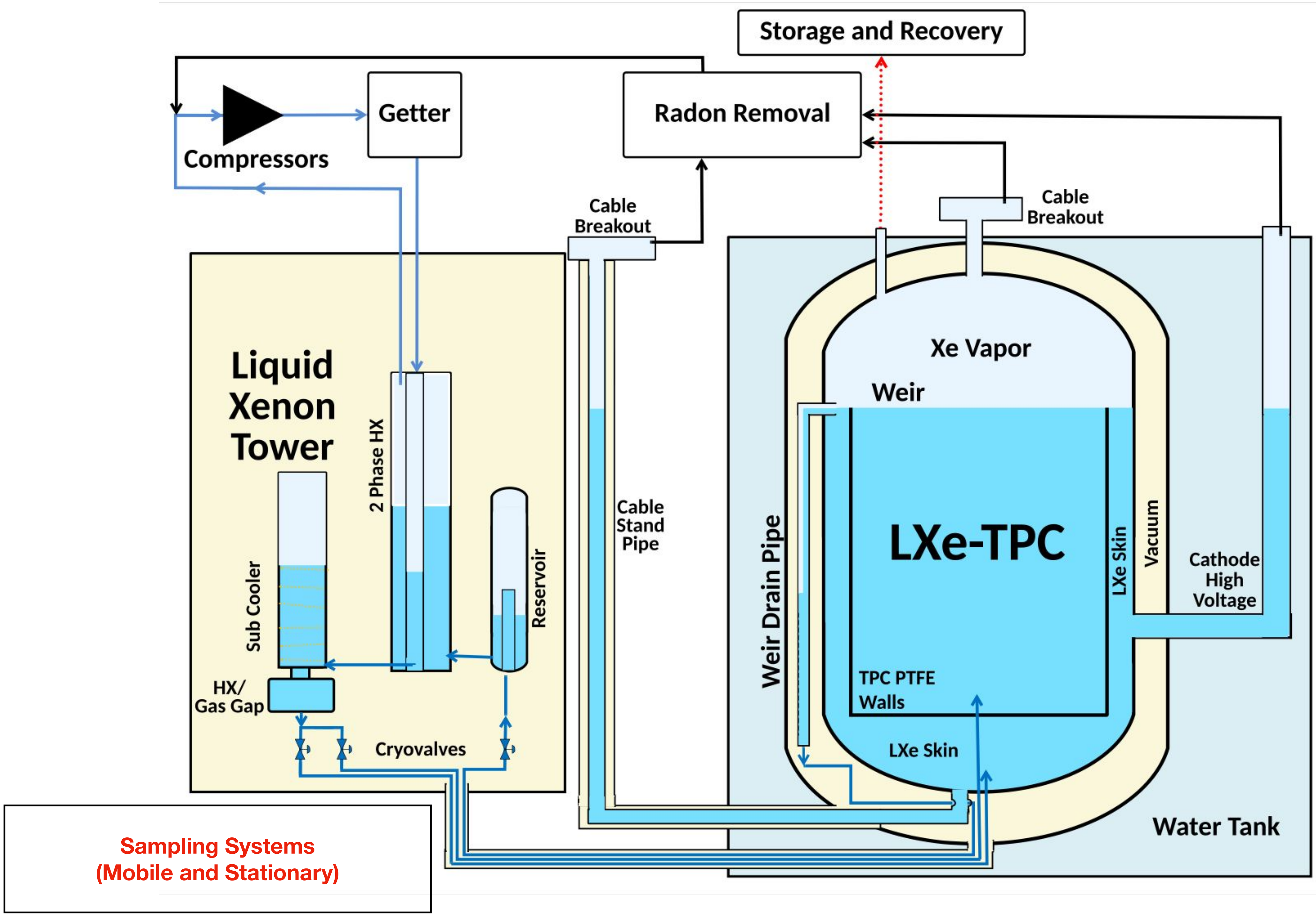








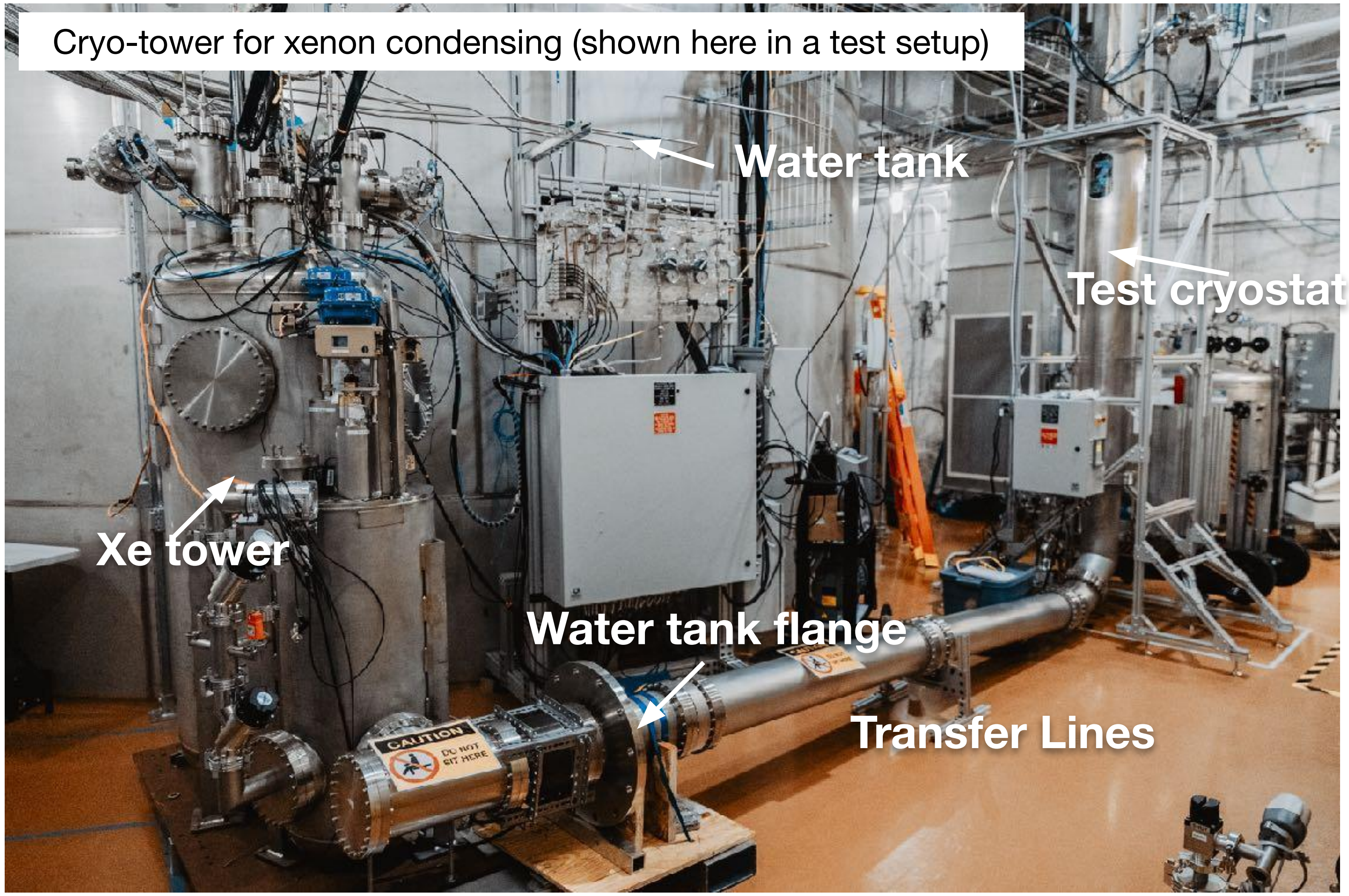
Xenon Circulation System



Time

Xenon Circulation System & Cryogenics Commissioning

- Design gas circulation rate: 500 slpm
  - Turnover full Xe mass every 2.4 days
  - Underground commissioning completed
    - Up to 600 slpm demonstrated
- Purification using hot zirconium getter
  - Removes non-noble impurities



LZ Physics Reach

- CEvNS
- Solar axions
- Axion-like particles (ALPs)
- Leptophilic dark matter
- Neutrino magnetic moment
- Mirror dark matter
- DM-EFT Couplings
- $2\nu\beta\beta$ of ^{134}Xe with competitive sensitivity to $0\nu\beta\beta$
- Sensitivity to the $0\nu\beta\beta$ decay of ^{136}Xe
- Enhanced sensitivity to low mass DM through Migdal effect
- Annual rate modulations
- And more!

[Phys. Rev. D 104, 092009 (2021)](#)
[Phys. Rev. C. 104, 065501 (2021)](#)
[Phys. Rev. C. 102, 014602 (2020)](#)